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May 2005 Working Group Meeting on Heavy Vehicle Aerodynamic Drag: Presentation, Summary of Comments and Conclusions

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May 2005
Working Group Meeting on
Heavy Vehicle Aerodynamic Drag:
Presentation, Summary of Comments, and Conclusions

Jointly written by

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University of Southern California, California Institute of Technology,

Auburn University, University of Tennessee Chattanooga,

NASA Ames Research Center, Georgia Tech Research Institute,

National Research Council of Canada

A Working Group Meeting on Heavy Vehicle Aerodynamic Drag was held at Lawrence Livermore National Laboratory, Livermore, California on May 12^{th} and 13^{th} of 2005. The purpose of the first day's meeting, May 12^{th}, was to provide a summary of achievements, discuss issues, present a general overview of future plans, and to offer a forum for dialogue with the Department of Energy (DOE) and representatives from industry, universities, and research and development organizations performing work related to heavy vehicle aerodynamics. This first meeting day was open to participants from industry and research organizations from both the US and Canada. The second day, May 13th, was attended only by representatives from the 9 organizations that form the DOE Consortium effort and their government sponsors. The purpose of the second day's meeting was to further discuss fiscal year 2005's activities, any further specific pressing issues, identify individual action items, and provide an overview of plans for fiscal year 2006.

Participating in the Working Group Meeting were representatives from the DOE/Office of Energy Efficiency and Renewable Energy/Office of FreedomCAR & Vehicle Technologies, members of the DOE consortium: Lawrence Livermore National Laboratory (LLNL), Argonne National Laboratory (ANL), Sandia National Laboratories (SNL), NASA Ames Research Center (NASA), University of Southern California (USC), California Institute of Technology (Caltech), University of Tennessee Chattanooga (UTC), (consortium members from Auburn University (Auburn) and Georgia Tech Research Institute (GTRI) were unable to attend), consortium collaborators from the National Research Council (NRC) of Canada, tractor manufacturer representatives: Mack Trucks, Inc./Volvo 3P, International Truck, and Kenworth/PACCAR, a representative from one of the largest national fleets, U.S. Xpress Enterprises, and a tire manufacturer, Michelin R&D, and others from universities, small companies, and other national laboratories. A complete list of participants can be found at the end of this summary section, along with the agendas for both meeting days. This report contains the technical presentations (viewgraphs) delivered each day, briefly summarizes the comments and conclusions, provides some highlighted items, and outlines the future action items.

Project Goals and Future Activities

Based on discussions at the Meeting, the existing project goals remain unchanged and enhancing interactions with fleet owners and operators was emphasized:

- Perform heavy vehicle computations and experiments,
- Validate computations using experimental data,
- Provide design guidance and insight into flow phenomena from experiments and computations, and
- Investigate aero devices with emphasis on collaborative efforts with fleet owners and operators.

The following future activities were identified, categorized as technical or administrative, and the responsible organizations are indicated:

Technical

1. Acquire paper on measure of aerodynamic drag from tire load, SAE 92-0346. (LLNL)
2. Acquire data on duals versus single tires, e.g., SAE II test data from GTRI. (DOE/ANL)
3. Check Kenworth/PACCAR website paper with recommendation on devices (LLNL)
4. Look at “hula” skirts (a flexible, porous device, possibly made of hanging string fibers, mounted on bottom sides of trailer): CFD-porous flexing plate, test- NRC or NASA (LLNL, NASA)
5. Consider benefits for reducing drag for hybrid vehicles. Check findings of large fleets (e.g., UPS). (USC, LLNL)
6. Consider open grate at base of gap (LLNL)
7. Investigate if baseflap and wedge counteract (LLNL)
8. Investigate if flow can be excited to improve baseflaps and effect of different flap angles (LLNL)
9. Investigate splash and spray with baseflaps and if visibility of brake lights could be hindered (LLNL)
10. Evaluate singularity points on rotating tire (UTC)
11. SAE Conference Chicago in Nov 2005 – Papers/abstracts/presentations (ALL), Invite as Consortium/National Lab representative on Aero Panel (LLNL/Kambiz S.), Invite as LLNL representative on Technology Panel (LLNL/Rose M.)

Administrative

1. Gather all viewgraphs from meeting (ALL send to LLNL)
2. Meeting with fleet owners, ATA, and others, possibly at SAE Conference, Chicago, Nov 2005 (LLNL – SOLUS is now coordinating meeting)
3. Contribute to 21CTP white paper on aero (LLNL)
4. Attend, present at 21 CTP aero merit review possibly in September (LLNL)
5. Join US Xpress Enterprises representative, Marty Fletcher, at an ATA, TMC, or TMA committee meeting (LLNL)
6. Sharing of DOE industry Consortium test plan (DOE)
7. Construct industry collaborative proposals to DOE’s 2007 RFP (ALL)
8. Address underhood cooling with aero-white paper or possible CRADA (NASA, LLNL, ANL)
9. Pursue joint government (DOE, DOT) and industry (Michelin) effort on wheel aero and splash & spray (USC, LLNL)
10. Industry incentives – talk to 21CTP Lead, Ken Howden (DOE)
11. Visit other big fleet operators, Fedex, UPS (LLNL, USC, NASA, UTC)

12. Find product engineers who can design devices or decide if need national labs to design (LLNL)
13. Ask NRC to test effectiveness of devices for braking (LLNL)
14. Meet with rail companies, railcar manufacturers, power companies (NASA)
15. Meeting with DOT & Bill Knee, ATA's Vic Suski (DOE)
16. Construct FY06 tasks/milestones and budget by mid July, determining high priority activities, considering expected budget cuts (LLNL).
17. Suggest people for ECI meeting to Dave Whitfield, UTC (ALL)

Meeting Summary

In this section, we briefly review the major results presented and discussed at the meeting, with a focus on new information not previously presented. See meeting agendas at the end of this section and attached viewgraphs for additional results and details.

Introduction

The meeting began with an introduction by the DOE Aero Consortium Lead, Rose McCallen (LLNL) and a welcome from LLNL's Energy Program Lead, Ray Smith (LLNL). LLNL's Associate Director, Jane Long, also provided a brief description of the Energy & Environment Directorate and a welcome to the meeting participants during Lunch. The DOE sponsor, Sidney Diamond (DOE), followed the introductions. Sid first mentioned that the DOE Consortium was formed 7 years ago at the first workshop held in Pheonix, Arizona to address aerodynamic drag of heavy truck vehicles. He also emphasized the benefits to reducing fuel consumption by heavy vehicles. Class 8 tractor-trailers consume 11% to 12% of the total U.S. consumption of petroleum.[1]

Jules Routbort (DOE/ANL) presented an overview of the 21st Century Truck Program for Ken Howden (DOE) who was unable to attend. Mike Laughlin (New West Technologies) also gave an overview of the activities of the newly formed DOE Industry Consortium for Bob Clark (TMA) who was unable to attend. The DOE Industry Consortium consists of Freightliner, International, Mack Trucks, and Volvo. They are investigating four major areas of Class 8 tractor-trailer drag reduction. Mike also provided some information on the Department of Transportation Re-Organization and the formation of the new Research Innovation Technology Administration (RITA) formed as part of the re-organization.

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[1] Per 2002 statistics in U.S. Department of Energy, Oak Ridge National Laboratory, Transportation Energy Data Book, 24th Edition (http://cta.ornl.gov/data/new_for_edition24.shtml), tractor-trailer combination vehicles drive 138.6 billion miles per year and consume 26 billion gallons of diesel fuel per year. If we assume that the refinement of a barrel of crude oil, provides about 70-80 percent diesel fuel, then the tractor-trailer crude oil consumption is 2.1 to 2.4 to million barrels per day (= 26 billion gal (1 barrel/42 gal) (1 yr/365 days) (1 barrel crude/0.7 to 0.8 barrel diesel)). The total US crude oil consumption is about 19.7 million barrels per day.

After these introductory and background presentations, an overview of the DOE Heavy Vehicle Aero Project and the Consortium's goals, objectives, and focus areas past, present, and planned for the future was presented by Rose McCallen (LLNL). This introduced the main part of the meeting consisting of three presentations to introduce the 3 topics for discussion:

- Achievements,
- Main issues, and
- Path forward.

Informal discussions followed each presentation (see agenda at end of this report, before the viewgraphs). Summaries of the discussion for all three topics were presented so that conclusions may be established. The highlights of the discussions are presented below and details are provided in the attached summary viewgraphs.

Also, during the working lunch, movie presentations were given on "Tire Aero & Splash/Spray" by Michelin Tire representative, Ralph Hulseman, and on a "Baseflap Device" by Norcan representative, Mathieu Boivin.

Achievements

Attached are the viewgraphs presented by Kambiz Salari (LLNL), providing an overview of the Program accomplishments. In summary, the Program has demonstrated several concepts and devices which meet the 25% drag reduction goal. Specific devices have addressed base, gap, and underbody drag reduction (Figure 1). Use of a simple base flap at the trailing edge of the trailer, side extenders or splitter plate at the tractor-trailer gap, and a skirt or a simple short underbody wedge should provide drag reduction exceeding 25%. At highway speeds, fuel savings around 12% should be recognized for a 25% reduction in drag. This would represent savings in the billions of dollars in the United States.

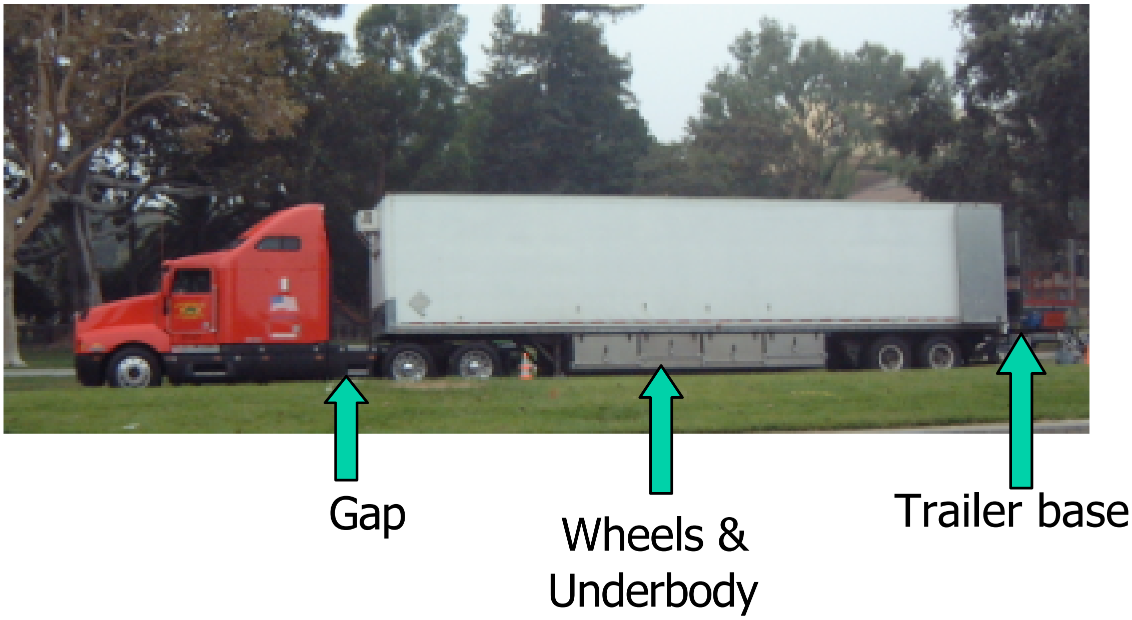

Figure 1. The major drag contributors are the trailer base, underbody, and gap drag.

The Consortium’s highly successful testing program has provided detailed data for computational validation, guidance on device concepts, and established wind-tunnel testing guidelines. The computational flow modeling has provided guidance in model definition, mesh refinement, and choice of turbulence model for heavy vehicles. Computations have been used for both the evaluation of flow physics and to guide the conceptual design of devices. The Program has successfully established industry contacts and collaborations and international recognition in the academic community.

The presentation of achievements was followed by a discussion session facilitated by Dave Whitfield (UTC). Viewgraphs summarizing the discussion were constructed and presented by Mike Rubel (Caltech) and John Paschkewitz (LLNL). The main discussion points included:

- NRC Canada has explored many of the presented device concepts and has performed full-scale testing. The Consortium should continue their pursuit of collaborative efforts with NRC.
- The Consortium needs to involve industry sooner in process to consider practical constraints, but at the same time should be forward-looking about technology changes. The participant from US Xpress Enterprises, Marty Fletcher, emphasized that the end user does dictate what devices are used and must consider maintenance, liability, and other issues. Operation issues include how individual devices for gap, underbody, and base interact. One suggested source of information is the American Trucking Association’s (ATA) advisory group which

consists of fleet operators. The need to put information out to the masses and presented for the general audience was emphasized.
- Underhood/thermal control needs to be considered, especially with upcoming 2007 EPA emissions regulations. Difficulty is lack of experimental data.
- Should report ΔCD as well as percent drag reduction, since base drag is so variable.
- Model fidelity is important. Flow through radiators should be considered in experiments and computations.

Main Issues

Attached are the viewgraphs presented by Jim Ross (NASA), providing a summary of the program's current, main issues for discussion. Tony Leonard (Caltech) facilitated the discussion and attached are the summary viewgraphs constructed and presented by Ramesh Pankajakshan (UTC) and Paul Castellucci (LLNL).

In summary, the specific topic areas presented were:

- Getting improvements on the road,
- Aerodynamic prediction capability, and
- Funding.

The following summarizes the opinions of the participants as to why the fleet owners and operators are not using the trailer devices and what can be done to encourage the use of drag reducing technology. Also included are some important points made during the discussion regarding computational and experimental predictive capability and funding.

Devices

- Engineering and marketing of devices is needed for immediate impact. Devices should be transferable and reusable.
- Data on device performance isn't readily available.
- There is an industry disconnect. For example, the trailer manufacturers are absent from the discussion/meetings.
- The operational restrictions that limit device use are needed. For example, could base flaps restrict brake light visibility and trailer access?
- Information on what has been tried and economic benefits is needed.
- It is unclear why the manufacturing industries have not integrated the tractor and trailer system.
- It is believed that rising fuel prices will force the issue.
- The Consortium needs to do more in sharing their R&D information with industry and getting the information in the public domain. For example, simple messages like don't go faster and don't idle if you want to reduce your fuel consumption.

Predictive Capability

- Reliability of computational fluid dynamics (CFD) is longer term.
- Keeping track of winds is important in comparing wind tunnel and road tests.
- The effect of a moving ground plan on the vortical structures and the forces and moments should be investigated.
- Considering open grill is critical for drag simulations and experiments. The effect of the open grill is important if trying to manage flow. For example, in the design of an aerodynamic bumper.

Funding

- DOE Collaborative Research and Development Agreements (CRADA) funding generally goes to the National Labs for collaboration with industry. Proprietary information can be protected in a CRADA.
- DOT may have interest in splash and spray
- OEM's and tire manufacturers don't get credit for reducing fuel consumption. For example, the EPA could provide credit for the associated reduction in emissions.
- DOE should encourage EPA's SmartWay Program to give credit for fleet operators using drag reducing devices.

Path Forward

Attached are the viewgraphs presented by Rose McCallen (LLNL), providing a brief summary of the program's "Path Forward". Also presented was a review of "Wheel Aero/Safety/Underhood – Drag, Brake Cooling & Splash/Spray" by Craig Eastwood (LLNL) and Fred Browand (USC), followed by a presentation of NRC Canada's work and future collaboration presented by Kevin Cooper (NRC) and Jason Leuschen (NRC). Larry DeChant (SNL) facilitated the discussion that followed the presentations. David Pointer (ANL) and Jason Ortega (LLNL) constructed and presented a summary of the discussion. All the viewgraphs are included at the end of this document.

The following are the five suggested future focus areas with a brief description.

Getting technology on the road: This will involve working with fleet operators, tractor manufacturers, especially those involved in the DOE Industry Consortium, and trailer manufacturers to encourage full-scale road testing of promising devices. These activities should be in collaboration with the full-scale testing being done at NRC Canada.

System integration: With the recognition of the ties between vehicle aerodynamics and safety issues related to brake cooling and tire/wheel splash and spray, joint DOE/DOT government activities will be pursued. The goal is reducing fuel use with enhanced safety.

Computational modeling that adequately captures reality: The computational modeling effort will pursue needed improvements in model scaling and fidelity, multi-physics modeling, and consideration of operational environment.

New areas: Tire/wheel aerodynamics with the investigation of brake cooling and splash and spray will be investigated both computationally and experimentally. Use of state-of-the-art computational tools and experimental diagnostics will be used to further the understanding of underhood thermal control, leading to conceptual design improvements. Support for continued investigations of railcar aerodynamics will also be pursued.

Funding: Attempts will be made to expand funding sources through government teaming and leveraging of funds.

The session on Wheel Aero/Safety/Underhood included presentations delivered by Craig Eastwood (LLNL) and Fred Browand (USC). Craig provided an overview of the computational work being performed at LLNL, UTC, and Caltech. Simulations of rotating wheels with increasing fidelity, splash models, and spray simulations around a truck model were described. The aerodynamics of rotating wheels is being considered not only for underbody aerodynamic drag, but also for the modeling of brake cooling and splash and spray. Preliminary splash simulations have been performed utilizing a volume-of-fluid surface tracking algorithm. Ongoing work involves the goal of simulating spray around an entire truck model include aerodynamic breakup, collisions, and preferential concentration effect. The success of the effort is dependent in part on the high-quality experimental data being provided by USC for both benchmarking and validation of the computational models, as well as the physical insight provided directly from the analysis of the experimental data.

As part of this same session, Fred Browand (USC) presented a detailed theoretical analysis of jet, sheet, and droplet formation for rotating tires. He showed some remarkable visualizations of jet, sheeting, and droplet formation and breakup. The results were from experiments being performed at USC with a new apparatus called the Tire Spray Simulator (TSS). The TSS has demonstrated its usefulness in creating realistic spray. Qualitative results have been obtained using a backlight and laser sheet procedures, leading to an understanding of some the mechanisms behind the formation of jets and sheets, and of the eventual formation of droplets. The next step in analysis will be to measure droplet size and droplet velocity as a function of position within the spray field. Droplet sizes within the spray field are of first importance in themselves, but size information is also needed to resolve the velocity field according to size. Plans are to evaluate droplet size in each image pair and filtering each image before the digital particle image velocimetry (DPIV) algorithms are applied. Local droplet size or local scale can be determined either by application of an image-segmenting technique or by application of a localized scale-filtering process such as a wavelet transform.

Also presented was a preliminary design idea by Consortium members from NASA for a 'separate flows for separate tasks' underhood flow/thermal control configuration. The design is inspired by the design of a Lancair 320 aircraft. The plans for a heavy vehicle engine is to provide separate air passages for radiator cooling air and for cooling of specific accessories. The proposed diagnostics include measured pressures throughout the engine compartment, use of temperature-sensitive paint for temperature measurement, and DPIV for velocity field information.

Representatives from NRC, Kevin Cooper and Jason Lueschen, described their collaborative experimental wind tunnel work. It was emphasized that their effort is a "non-competitive, non-commercial program" that is "not intended to invent products" but is instead "designed to transfer technology to benefit truckers & country." NRC is aligning their work with the DOE program to leverage the investment by their funding source, National Resources Canada. The goal is to test common hardware, exchange wind tunnel and road data, share hardware where possible, and interface with OEMs. Their current wind tunnel results show that trailer skirts, trailer base mounted boattails, and tractor side extenders are the most promising.

Overview of Second Day

The presentations on the second day, May 13th, provide more detailed, technical information on topics including drag reducing concepts, with related safety enhancements. Also included were presentation summarizing conclusions from the first day meeting and future activities.

Truck Aero Team Meeting Attendees

Lawrence Livermore National Laboratory, Livermore, CA

May 12, 2005

Attendee	Organization	e-mail address and phone
Salvador Aceves	LLNL	aceves6@llnl.gov
Mathieu Boivin	Norcan	mboivin@norcanalu.com
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Alec Wong	Kenworth/PACCAR	awong@paccar.com
Rick Wood	SOLUS LLC	rick@solusinc.com

AGENDA

Heavy Vehicle Aerodynamic Drag: Working Group Meeting

Lawrence Livermore National Laboratory, Livermore, CA

B170, Rm 1091 & 1092

May 12, 2004

Purpose of Meeting

Sharing of information & discussion of issues to define our path forward

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Introduction

7:45—8:15AM	Continental Breakfast	
8:15—8:30AM	Introduction, safety, security	Rose McCallen (LLNL)
8:30—8:45AM	Welcome to LLNL	Ray Smith (LLNL)
8:45—9:00AM	Words of Wisdom	Sid Diamond (DOE)
9:00—9:15AM	21st Century Truck Program	Jules Routbort for Ken Howden (DOE)
9:15—9:30AM	DOE Industry Consortium	Mike Laughlin for Bob Clarke (TMA)
9:30—9:45AM	Re-org: Research Innovation Technology Administration	K. Thirumalai (DOT)
9:45—10:00AM	**DOE Heavy Vehicle Aero Project** - Overview	Rose McCallen (LLNL)
10:00— 10:15AM	**Break** (15 min)	

Achievements

10:15— 10:45AM	Exp. & Comp. Directed Drag Reduction Devices (30 min)	Kambiz Salari (LLNL)
10:45— 11:15AM	Facilitated Discussion (30 min) – informal	Dave Whitfield (UTC)
11:15— 11:30AM	**Break** (15 min)	
11:30— 11:45AM	Summary (15 min)	Mike Rubel (Caltech), John Paschkewitz (LLNL)

Main Issues

11:45— 12:00PM	Presentation of Issues (15 min)	Jim Ross (NASA)
12:00— 12:30PM	Facilitated Discussion (30 min) – informal	Tony Leonard (Caltech)
12:30— 1:45PM	**Lunch** (45 min)	
	Tire Aero & Splash/Spray Movies (15 min)	Ralph Hulseman (Michelin)
	Baseflap Device	Mathieu Boivin (Norcan)
	LLNL's Energy & Environment Directorate	Jane Long (LLNL's Associate Driector)
1:45— 2:00PM	Summary (15 min)	Ramesh Pankajakshan (UTC), Paul Castellucci (LLNL)

Path Forward

2:00— 2:15PM	Presentation on Path Forward (15 min)	Rose McCallen (LLNL)
2:15—2:45PM	Wheel Aero/Safety/Underhood – Drag, Brake Cooling & Splash/Spray	
	Computations – LLNL, UTC, Caltech (15 min)	Craig Eastwood (LLNL)
	Experiments – USC (15 min)	Fred Browand (USC)

2:45—3:00PM	Collaborations with Canada (15 min)	Kevin Cooper (NRC), Jason Leuschen (NRC)
3:00— 3:30PM	Facilitated Discussion (30 min) – informal	Larry DeChant (SNL)
3:30—3:45PM	**Break** (15 min)	
3:45—4:00PM	Summary (15 min)	David Pointer (ANL), Jason Ortega (LLNL)
6:00—7:00PM	**Dinner (no-host) – Pastas Trattoria, 4040 East Ave, Livermore**	
7:00—7:15PM	Discussion, wrap-up	Sid Diamond (DOE), Rose McCallen (LLNL)

AGENDA

Heavy Vehicle Aerodynamic Drag: Working Group Meeting

Lawrence Livermore National Laboratory, Livermore, CA

B543, Grand Canyon Room

May 13, 2004

Purpose of Meeting

1. Discuss activities, pressing issues
2. Overview of FY06 plans, budget

Introduction

8:00—8:30AM	Continental breakfast	
8:30—9:00AM	Review of key items from previous day (30 min)	Fred Browand (USC)/Craig Eastwood (LLNL)
9:00—9:30AM	Discussion on previous day – facilitated (30 min)	Jim Ross (NASA)

Current FY05 Activities & Pressing Issues (~15 min presentations, ~15 min discussion)

9:30—9:40AM	Introduction & Objective (10 min)	Rose McCallen (LLNL)
9:40—10:30AM	HV Devices (50 min)	Jason Ortega/Paul Castellucci (LLNL)
10:30— 10:45AM	**Break**	
10:45— 11:15AM	Other Devices (30 min)	Bruce Storms (NASA)
11:15— 12:00PM	Safety – Splash & spray, brake cooling (45 min)	Ramesh Pankajakshan (UTC)/John Paschkewitz (LLNL)
12:00— 1:30PM		**Lunch (1 hr)**

Wrap-up

1:30— 3:30PM	Summary of action items, wrap-up (1 hr)	All

Viewgraphs from May 12, 2005 meeting in order of presentation

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

freedomCAR & vehicle technologies program

21st Century Truck Partnership

May 12, 2005

Kenneth C. Howden
Office of FreedomCAR and Vehicle Technologies (FCVT)
Energy Efficiency and Renewable Energy
U.S. Department of Energy

21CTP

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Outline of Presentation

- Vision for the Partnership
- Organization of Partnership
- Activities of Partnership
- R&D Goals of 21CTP
- DOE 21CT Research Priorities

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

21st Century Truck Partnership

"The progress we are making in heavy truck technology under the 21st Century Truck Partnership will provide the United States with significant efficiency and safety benefits, and cleaner air, while helping to maintain America's international competitiveness in this key industry sector."

Energy Secretary Bodman speaks at the 21st Century Truck Partnership event at SAE Government Industry Meeting in Washington, D.C. on May 10, 2005

21ST CENTURY TRUCK PARTNERSHIP

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

21CTP Addresses National Imperatives

Transportation in America supports:

- the *growth of our nation's economy* both nationally and globally,
- the country's goal of *energy security.*
- an *agile, well-equipped, efficient military force* capable of rapid deployment and sustainment anywhere in the world.

Transportation in our country is *clean, safe, secure, and sustainable.*

Our nation's transportation system is compatible with a *dedicated concern for the environment.*

21ST CENTURY TRUCK PARTNERSHIP

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

21st Century Truck: A Government-Industry Partnership

Allison Transmission
BAE SYSTEMS
CATERPILLAR
Cummins
DaimlerChrysler
Detroit Diesel Corporation
EATON
Freightliner LLC
A DaimlerChrysler Company
Honeywell
21st Century Truck Partnership
International
Mack
NovaBus
Oshkosh
PACCAR
Volvo
New Roads.

DOE / EE
FreedomCAR and Vehicle Technologies

DOD / Army
TACOM NAC
Military Vehicle R&D

DOT / RSPA
Intelligent Vehicle and Highway Safety R&D

EPA
Vehicle Emissions Regulations

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Partnership Coordination

- ❑ "Face to face" meetings
  - Full Group (6 per annum)
  - Sectors – Engine, Hybrid, Truck OEM (2 each per annum)
- ❑ Biweekly teleconferences
  - Government
  - Industry
  - Combined government/industry
- ❑ Focus area white papers (five)
- ❑ Login protected web-site
- ❑ Project inventory (searchable database)

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Energy Efficiency and Renewable Energy
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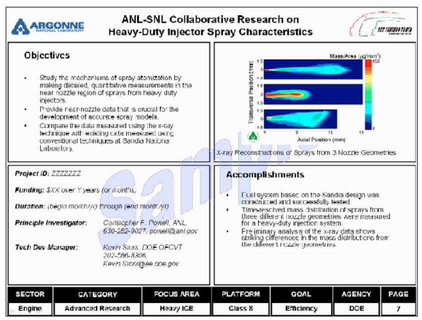
Additional Resources (in development)

- ❑ Non-partner collaboration plan
- ❑ Book of project one-pagers
- ❑ Technical validation plan
- ❑ Public web-site


ANL-SNL Collaborative Research on Heavy-Duty Injector Spray Characteristics

Objectives

- Study the mechanisms of spray atomization by making detailed, quantitative measurements in the near nozzle region of sprays from heavy duty injectors.
- Provide near-nozzle data that is crucial for the development of accurate spray models.
- Compare the data measured using the x-ray technique with existing data measured using conventional techniques at Sandia National Laboratory.

X-ray Reconstructions of Sprays from 3 Nozzle Geometries

Project ID: *ZZZZZZZ*

Funding: *$XX over Y years (or months)*

Duration: *(begin month/yr) through (end month/yr)*

Principle Investigator: *Christopher F. Powell, ANL, 630-252-9027, powell@anl.gov*

Tech Dev Manager: *Kevin Stork, DOE OFCVT 202-586-8306, Kevin.Stork@ee.doe.gov*

Accomplishments

- Fuel system based on the Sandia design was constructed and successfully tested.
- Time-resolved mass distribution of sprays from three different nozzle geometries were measured for a heavy-duty injection system.
- Preliminary analysis of the x-ray data shows striking differences in the mass distributions from the different nozzle geometries.

SECTOR	CATEGORY	FOCUS AREA	PLATFORM	GOAL	AGENCY	PAGE
Engine	Advanced Research	Heavy ICE	Class 8	Efficiency	DOE	7

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Partnership RD^3 Focus Areas

Technology goals focus on five key areas for heavy duty vehicles

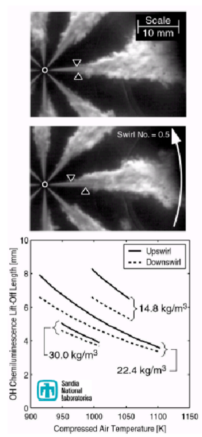
- ❑ Engine Systems
- ❑ Heavy-Duty Hybrids
- ❑ Parasitic Losses
- ❑ Idle Reduction
- ❑ Safety

Support Research, Development and Demonstration

21CTP Engine Systems Goals

Improve Efficiency of Engine Systems

- Improve Class 7- 8 brake thermal efficiency to 50% by 2010
- Research and develop technology to achieve 55% efficient prototype by 2012
- Explore new diesel fuel specs using renewables and non-petroleum-based fuels to displace 5% of petroleum by 2010

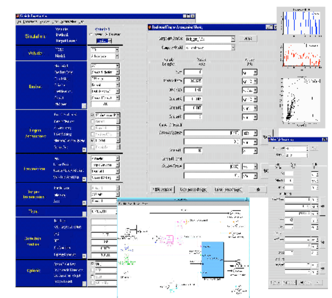


21CTP Heavy Hybrid Goals

Reduce Heavy Hybrid Component Costs to Promote Market Penetration

- Develop new generation of drive units with higher specific power, lower cost and durability matching service life of vehicle (15 yr design life) for under $50/kW by 2012
- Develop energy storage systems with 15 yr. design life, that prioritize higher power vs. higher energy, costing under $25/kW by 2012
- Develop and demonstrate 2007 emissions-compliant heavy hybrids with 60% fuel economy improvement on an urban driving cycle

Rapid Automotive Powertrain Simulator - Truck Simulation Model (RAPTOR-TSM) was used for performance and fuel economy analysis



United States Army NAC National Automotive Center

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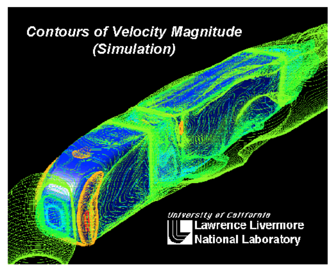
21CTP Goals for Mitigating Parasitic Losses

Reduce Parasitic Losses to Regain Horsepower in Class 8 Trucks

- ❑ Demonstrate 20% reduction in heavy vehicle drag coefficient by 2012
- ❑ Demonstrate 50% reduction in essential aux. power loads on heavy vehicle by 2012
- ❑ Validate 15-20% weight reduction in Class 8 tractor-trailer through materials optimization



21ST CENTURY TRUCK

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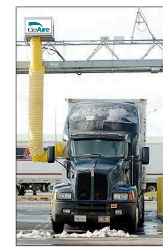
21CTP Idle Reduction Goals

Reduce Idling Fuel Use and Emissions by 85%

- ❑ Demonstrate and demonstrate advanced 5 kW auxiliary power units (APUs) that are quiet, weigh <200 lb, consume <0.25 gal/h diesel fuel @ full load and meet Tier 2 Bin 10 emissions for under $200/kW by 2007
- ❑ Develop and demonstrate 5-30 kW *fuel cell* APUs that use multiple fuels and operate at > 35% efficiency for under $400/kW by 2012
- ❑ Develop new codes and standards for electrification of trucks and truck stops



SmartWay™ Transport Partner
Getting There With Cleaner Air

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21CTP Safety Goals

Contribute to Reducing Truck-related Fatalities by 50% (vs.1996) through Safer Trucks

- Improve crashworthiness at highway speeds through better materials and vehicle design
- Improve crash avoidance for trucks through better braking, rollover stability and visibility

Static tilt table test to assess rollover stability

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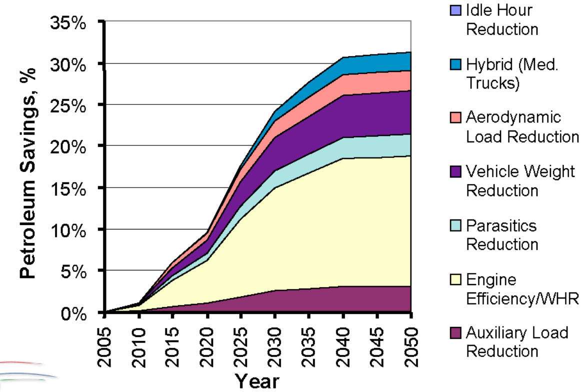
Petroleum Savings by Technology

Engine Efficiency/Waste Heat Reduction and Vehicle Weight Reduction contribute the most to CL 7&8 petroleum savings



GPRA 06 FCVT Heavy Vehicle Benefits, Preliminary Results, TA Engineering

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Merit/Peer Review Schedule

	Merit Review Topic	White Paper	Gov. Agency
Engine	Engine, Combustion & Emission Control	Engine Systems	DOE, EPA, DOD
Engine	Fuels Technology	Engine Systems	
Engine	Propulsion Materials	Engine Systems	DOE
Hybrid	Subsystem Integration and Development, Energy Storage, Advanced Power Electronics	Heavy-Duty Hybrids	DOE, EPA, DOD
Truck OEM	Vehicle Systems (Aerodynamic Drag, Rolling Resistance, Thermal Management, Friction, Wear)	Parasitic Losses	DOE
Truck OEM	High-Strength Weight Reduction Materials	Parasitic Losses	DOE
Truck OEM	Idle Reduction (Automatic Start/Stop Systems, Auxiliary Power Units, Truck Stop Electrification)	Idle Reduction	EPA, DOE
Truck OEM	Crash Avoidance, Crash Worthiness	Safety	DOT
Truck OEM	Advanced Systems & ITS	Safety	DOT

2005: J F M A M J J A S O N D — 2006: J F M A M June

External Peer Review

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Partnership Accomplishments

- Defined 21CTP Vision
- Completed Project Inventory
- Established Technology Focus Teams
- Drafted "White Papers" in each Technical Area
- Established Goals for each Technical Area
- Established 21CTP website to disseminate information and share data

Assistant Secretary David Garman announcing 21CT Goals at SAE Government-Industry Meeting May 2003

Exhibit at EPA/DOE Idle Reduction Conference, May 2004

- Co-sponsored Idle Reduction Conference with EPA, May 2004
- Organized Heavy Duty Vehicle Display at 2004 and 2005 SAE Government - Industry Meetings

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21ST Century Truck
– Moving Forward
21st Century Truck Heavy Duty Vehicle Display, SAE Government/Industry Meeting, May 2005, Washington, DC
21ST CENTURY TRUCK

Truck Manufacturers Association Aerodynamic Drag Project with DOE/NETL

Mike Laughlin
New West Technologies, LLC
-for-
Robert Clarke, President
Truck Manufacturers Association

Overview

- TMA Description and Management
- Project Partners
- Activities in this Project
- Contacts for More Information

TMA Overview

- TMA represents manufacturers of Class 6-8 trucks in North America
- TMA offers "one-stop shop" access to key HD manufacturers
- TMA role is to foster information sharing in this project to the extent possible while protecting intellectual property interests
  - Maximize benefits of project activities to all parties

3

Project Partners

- Project includes four key truck OEMs who will be doing the aerodynamic research
  - Freightliner LLC
  - International Truck and Engine Corporation
  - Mack Trucks, Inc.
  - Volvo Trucks North America, Inc.

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Project Overview

- Partners are researching effects on Class 8 truck aerodynamics of these areas:
  - Mirror design
  - Aerodynamic treatments of tractor trailer gap, trailer side, and trailer wake
  - Trailer aerodynamics, trailer gap enclosure, and trailer gap flow control
  - Vehicle underside design and management of tractor-trailer air flows
- Each participating manufacturer is taking a lead role in one of these four areas
- Results shared through normalized fuel economy and/or drag coefficient improvements on percentage basis
- Project duration of two years (October 2004-September 2006

5

Mirror Design

- Research effects of mirror design and configuration on aerodynamic performance through:
  - Computational fluid dynamics
  - Wind tunnel testing of full-scale trucks (drag measurements and flow visualization)

6

Trailer Gap/Side/Wake

- Address tractor trailer gap closure, trailer side enclosure, and trailer wake
  - Scale model wind tunnel testing of all promising concepts
  - Full-scale testing of best concepts with on-road vehicle testing in field

Trailer Aerodynamics/Gap Enclosure/Gap Flow Control

- Examine trailer-specific aerodynamic aids; gap enclosure systems; and gap flow control methods
  - Focus on road testing of concepts to bridge gap between CFD modeling and full-scale vehicle operation
  - Work with CFD modelers to characterize effects of aero concepts
  - Use SAE fuel economy testing to determine overall effects

Vehicle Underside/Management of Tractor-Trailer Air Flows

- Examine systems that manage vehicle underside air flow and systems that direct air flows in the tractor trailer gap
  - Main focus is underside air flow
  - Characterize effects through real-time fuel economy data on test loop

9

TMA Track Test Day

- Vehicles from this project will be displayed at a test track at end of project
- Discuss and demonstrate project successes
- Track location to be determined

10

Current Progress

- Contractual negotiations virtually complete
- Second draft of test plan describing overall research is being reviewed at NETL
- Project partners commencing research efforts

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Questions or Comments

- Overall project lead for TMA is
  - Robert M. Clarke, President (202-638-7825, robertmclarke@earthlink.net

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Achievements

Heavy Vehicle Drag Reduction Program

Kambiz Salari

Heavy Vehicle Aerodynamic Drag Working Group Meeting

May 12, 2005

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

Acknowledgements

Rose McCallen, Jason Ortega, Craig Eastwood, John Paschkewitz, Paul Castellucci

Fred Browand

Dave Whitfield, Ramesh Pankajakshan

Anthony Leonard, Mike Rubel

James Ross, Bruce Storms

Robert Englar

David Pointer

Collaborator: Kevin Cooper, Jason Leuschen

2

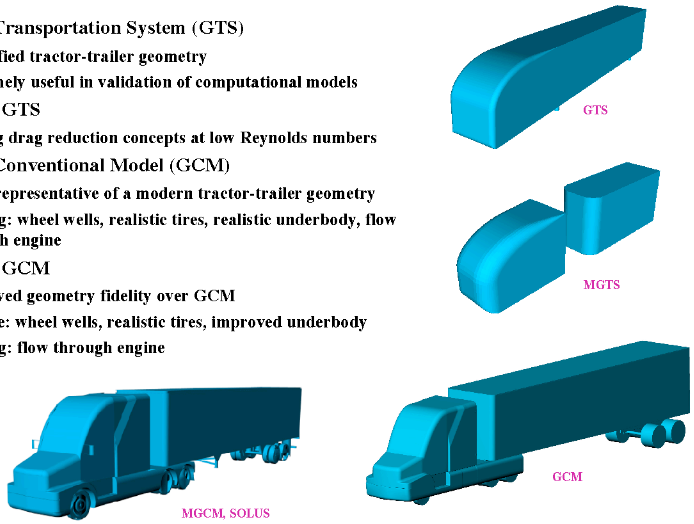
Goal: Reduce heavy vehicle drag by 25%

Approach:

- **Identify major contributors to drag**
  - Experimental discovery and testing
  - Modeling and simulations
- **Design drag reducing add-on devices**
  - Utilize accumulated knowledge gained in both experiments and simulations
- **Evaluate and test add-on devices using**
  - Experiments
  - Modeling and simulation
  - Track test
  - Road test
- **Get drag reducing add-on devices on the road**
  - Assist with operational and design concerns

Heavy vehicle models are used with increasing realism to understand the flow physics

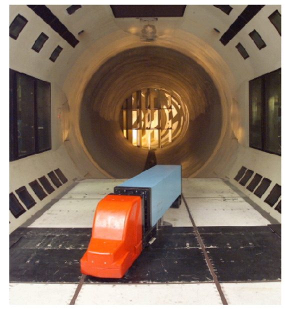
- Ground Transportation System (GTS)
  - Simplified tractor-trailer geometry
  - Extremely useful in validation of computational models
- Modified GTS
  - Testing drag reduction concepts at low Reynolds numbers
- Generic Conventional Model (GCM)
  - More representative of a modern tractor-trailer geometry
  - Missing: wheel wells, realistic tires, realistic underbody, flow through engine
- Modified GCM
  - Improved geometry fidelity over GCM
  - Include: wheel wells, realistic tires, improved underbody
  - Missing: flow through engine



Extensive experimental testing was performed on increasingly higher fidelity heavy vehicle models

NASA Ames Research Center

- 3'x4' wind tunnel, GTS, MGTS
  - 300,000 Reynolds number
  - Testing trailer base and underbody drag reducing concepts
- 7'x10' wind tunnel, GTS, MGTS, GCM
  - 2 million Reynolds number
  - Testing drag reducing concepts and flow physics
- 12' pressure wind tunnel, GCM
  - Full-scale Reynolds number is achieved!
  - Several drag reducing aero-devices were tested



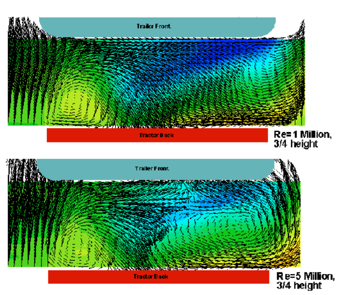
NASA Ames 12' pressure wind tunnel

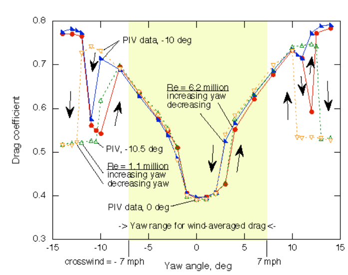
University of Southern California (USC)

- 3'x4' wind tunnel, MGTS
  - 300,000 Reynolds number
  - Testing gap and trailer base drag reducing devices and flow physics

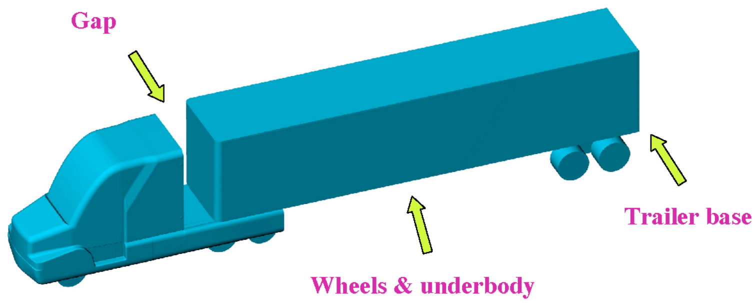
Significant knowledge was gained through experimental testing

- Improved understanding of flow physics
- Generated comprehensive data set for computational validation
  - Wind averaged aerodynamic forces
  - Surface pressure, steady and time dependent
  - Flow visualization, Particle Image Velocimetry
- Demonstrated Reynolds number effects
  - Reynolds number effects were relatively small above ~1.5 million.
  - Care should be taken in interpreting smaller-scale data





Critical drag producing regions were identified



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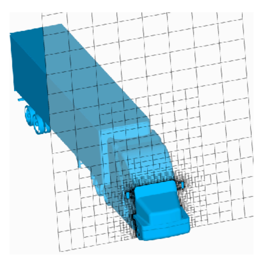
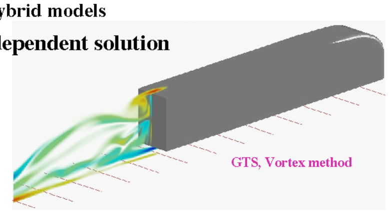
A variety of computational approaches were investigated

- **Navier-Stokes formulation, steady and time-dependent solutions**
  - Discretization schemes, FD, FV, and FEM method
  - Turbulence modeling, RANS, LES, and hybrid RANS/LES
  - Structured, unstructured, and overset meshes
  - Boundary representation
    - Boundary fitted
    - Cartesian mesh with trim cells to fit boundaries
    - Cartesian mesh with immersed boundary technique
- **Vorticity equation formulation, time-dependent solution**
  - Meshless, requires only a surface mesh
  - Turbulence modeling, LES, DNS, and hybrid models
- **Lattice Boltzmann formulation, time-dependent solution**



Immersed boundary method



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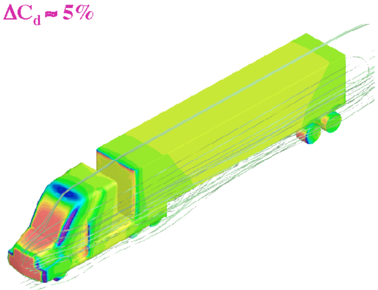
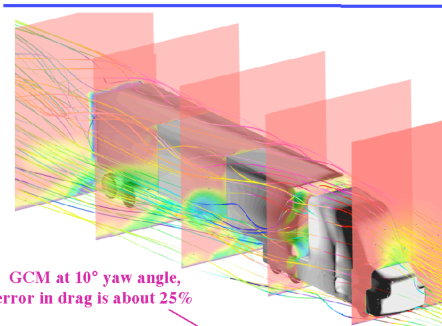
Guidelines were established for accuracy of computational predictions

Prediction of aerodynamic forces and the flow field are significantly influenced by

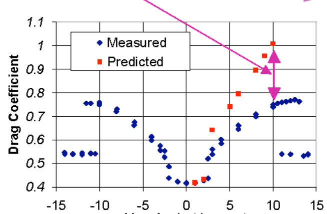
- **Geometry characteristics, $\Delta C_d \approx 15\%$**
- **Turbulence modeling selection, $\Delta C_d \approx 5\%$**
- **Grid resolution, $\Delta C_d \approx 10\%$**
- **Large yaw angles, $\Delta C_d \approx 25\%$**

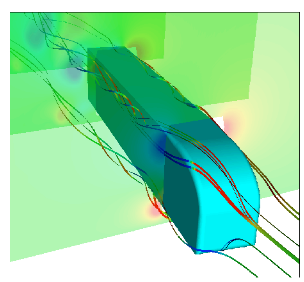


Computational prediction at large yaw angles requires extra care

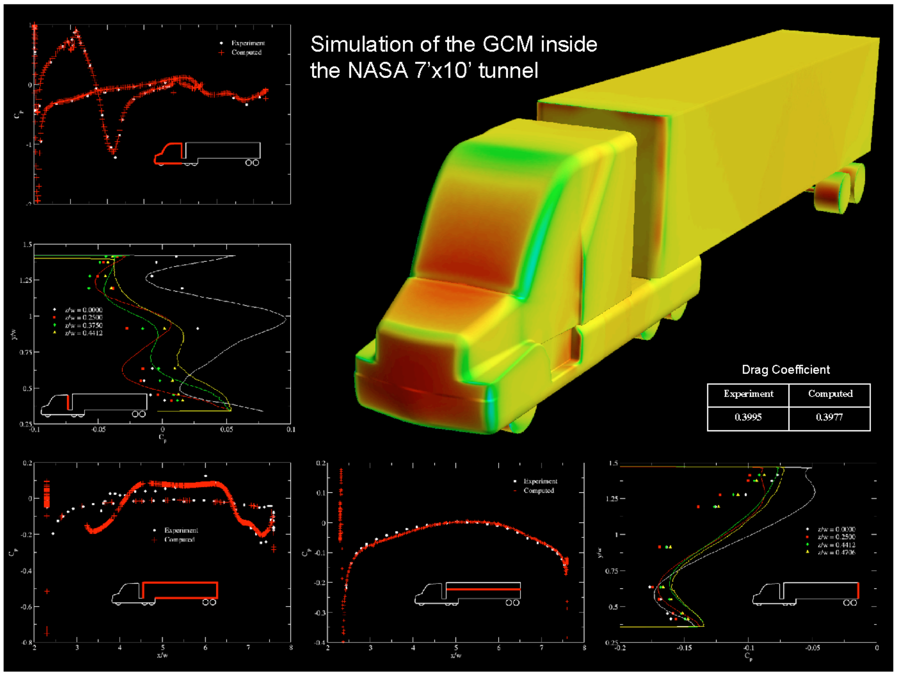


GCM at 10° yaw angle,
error in drag is about 25%





GTS at 10° yaw angle,
error in drag is about 5%

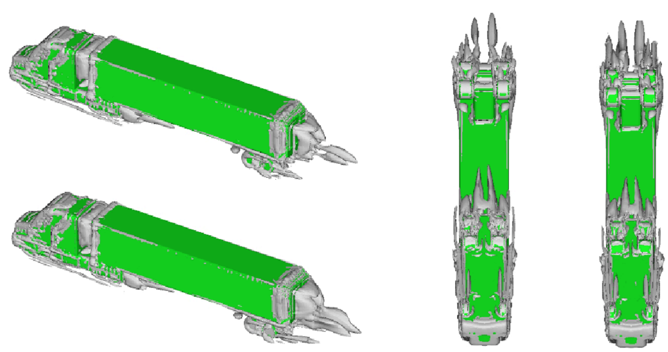


Influence of wheel rotation on drag ($\Delta C_d = 4.5\%$)

URANS simulation of GCM with rotating wheels at 0° yaw

URANS – No rotation

URANS – Rotation



URANS – No rotation

URANS – Rotation

Configuration	C_d at 0° yaw
Baseflaps w/ no wheel rotation	0.422
Baseflaps w/ wheel rotation	0.441 (+4.5%)

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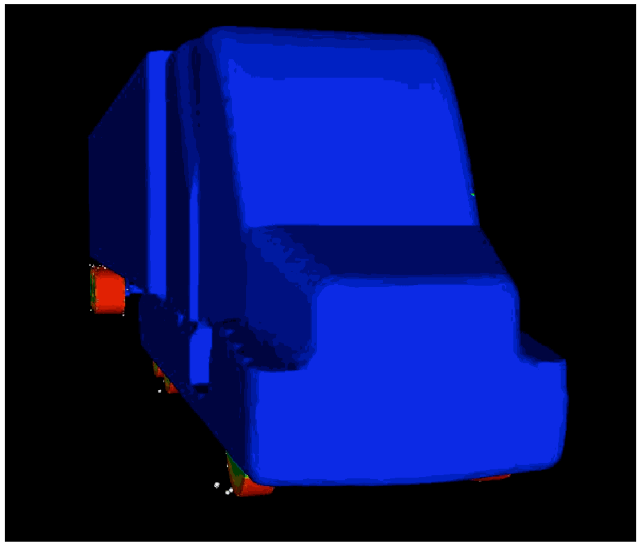
URANS simulation of GCM with rotating wheels



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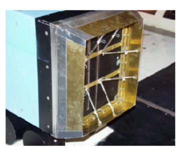
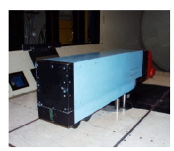
A variety of drag reducing add-on devices are tested

- **Trailer base**
  - Base flaps
  - Boat-tail plates
  - Base blowing
  - Ogive boat-tail
- **Underbody**
  - Belly box
  - Side skirt
  - Wedge
- **Gap**
  - Splitter plate

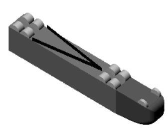


Base flaps

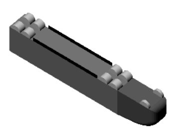
Boat-tail plates



Belly box

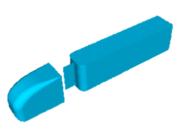


Wedge

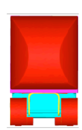


Side skirt

Base blowing



Splitter plate



Ogive boat-tail

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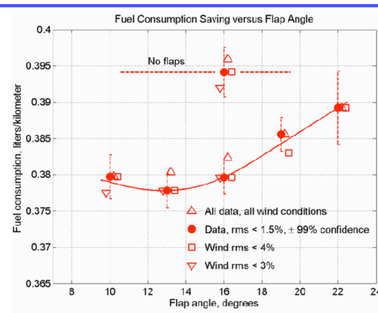
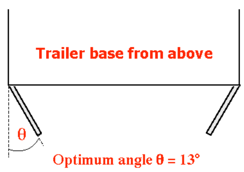
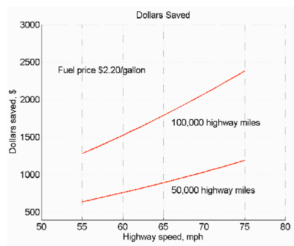
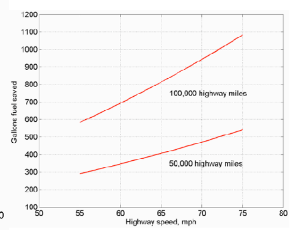
Base flaps tested at Crows landing (ΔC_d = -8.6%)









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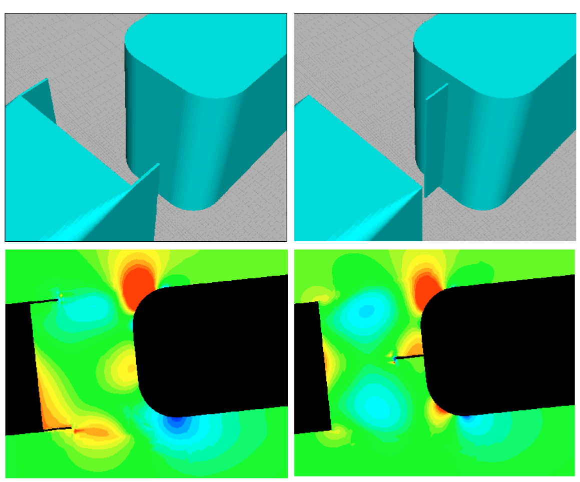
Gap add-on devices reduce drag by ~5%

The trailer splitter plate reduces drag without a significant increase in side force.



MGTS model,

6° yaw,

non-dimensional gap of 0.65,

Re = 340,000

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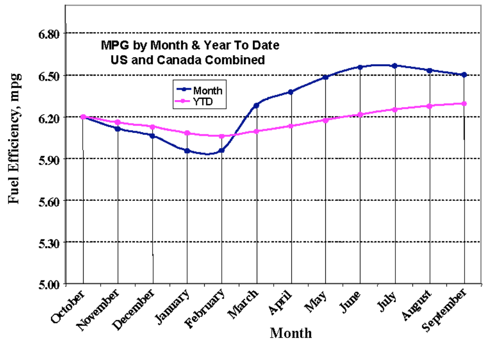
Effect of climate variation on aerodynamic drag

Seasonal variation in fuel efficiency



$$\text{Drag} = 1/2\ \rho\ V^2\ C_D$$

ρ = air density
V = wind speed over truck
C_D = drag coefficient

About 50% of the observed fuel efficiency variations can be attributed to wind and temperature variation during the year

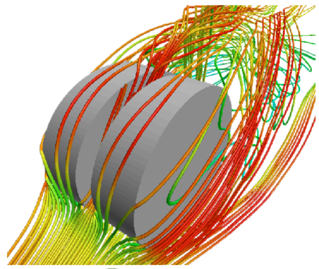
- Change in air density has the largest effect

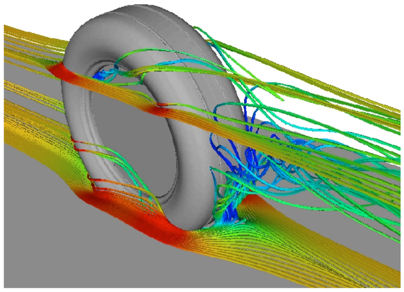
New initiatives related to safety

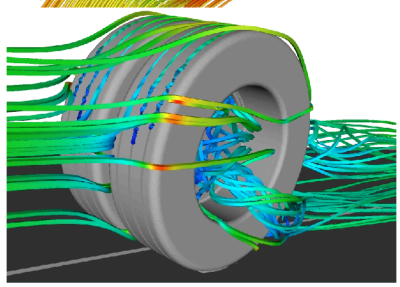
- **Splash and spray**
  - Tire aerodynamics
  - Experimental investigation at USC
- **Empty coal car aerodynamics**
  - Drag reduction concepts
- **Wind-induced overturning**

Flow field around tires is essential for spray formation and propagation

- Tire and wheel geometry significantly influences flow structures
- Spray transport is coupled to aerodynamics







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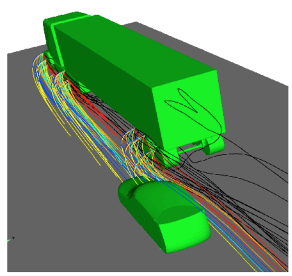
Develop modeling capabilities for splash and spray

- Goal
  - Understand important physics using state-of-the-art multiphase modeling tools coupled to realistic flow solutions
  - Explore various mitigation concepts
  - Design and test devices
- Challenges
  - Unsteady flow
  - Complex geometry
  - Splash and spray formation/interaction
- Advantages
  - Expertise
  - Resources
    - Simulation tools
    - Computer hardware



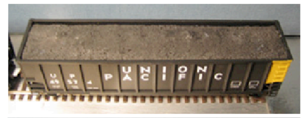
Particle trajectories around a truck and impact on passing car

20

Investigate empty coal car aerodynamics

- 2002 U.S. Statistics on coal usage*
  - 1 billion tons used, 66% carried by rail
  - 44% tonnage, 25% loads, 21% revenue
  - 85% by unit trains (50+ cars)
  - Average coal haul = 696 miles
- Aero Drag Reduction Potential
  - Fuel consumption: empty ≈ full
  - Aero drag ~ 15% of round-trip fuel consumption
  - 25% reduction → 5% fuel savings (75 million gal)

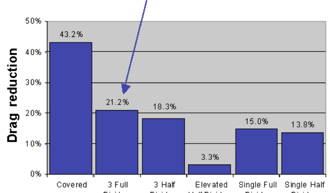
* The Rail Transportation of Coal, AAR, Vol. 5, 2003

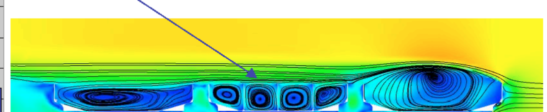


Designed drag reducing devices for an empty coal car

Add-on device

NASA Ames wind tunnel





Simulation, particle traces

Summary

- Extensive experimental testing was performed on increasingly higher fidelity heavy vehicle models
- Improved understanding of flow physics was obtained through knowledge gained with experimental testing
- Applicability of a variety of computational approaches to bluff body aerodynamics were investigated
- Established guidelines for accuracy of computational prediction
- Immersed boundary method can offer significant speedup in meshing complex geometries
- URANS simulations were performed on GCM with base flaps including the influence of rotating wheels
- Base flap and gap splitter plate were tested using modeling and simulations
- Starting to develop modeling and simulation capabilities for splash and spray that include tire aerodynamics
- Designed and tested drag reducing add-on devices for empty coal cars

23

Achievements: Summary

GOAL: 25% Drag reduction

Perhaps changes in Cd are adequate (?)

- Experimental tests with increasingly detailed models have illustrated Re effects and important flow physics
  - Need to consider even higher fidelity models (for example underhood effects)
- Full scale testing of devices has shown effectiveness of base flaps
- Simulations have been done with variety of computational approaches

Achievements: Summary (Simulations)

Guidelines for simulations have been established

- Need to exercise care in geometry, meshing, & turbulence model especially for high yaw angles
- Mesh generation is challenging – consider other methods that eliminate this issue such as IB, vortex or lattice Boltzmann (Powerflow).
- Integrated quantities can be misleading, need to be careful!
  - Ex: base pressure is wrong then drag reduction due to base modification is likely wrong
- Should consider unsteady and wheel rotation effects in CFD
- Considering other areas such as safety (splash & spray) and coal cars.
  - Safety: modeled wheel aero and exploring spray
  - Coal: Illustrated PRACTICAL DR concepts

Achievements: Summary

- Discussion highlighted many issues for path forward:
  - NRC Canada has explored many of these concepts & full-scale testing; should collaborate
  - Need to involve industry sooner in process to consider practical constraints, but at same time should be forward-looking about tech changes
  - Underhood/thermal control needs to be considered (emissions regs) but hard since temp data not avail.

Heavy Vehicle Drag Reduction Issues

- Getting improvements on the road
- Aerodynamic prediction capability
- Money…

Supporting the NASA Mission

Getting Improvements on the Road

- Testing requirements/standards
  - SAE Type 1 road tests mandatory?
  - Can fuel-flow meter readings or other test procedures be developed that would be acceptable?
  - Can CFD and/or wind tunnel results suffice?
- Operator/driver reluctance
  - Time required to operate devices
  - Reliability and damage tolerance
- Regulatory vs. economic incentives
  - Will the current high fuel prices start a trend?

Aerodynamic Prediction Capability

- Flow physics modeled accurately?
  - Wake
  - Gap
  - Underbody, wheels/tires, & road
  - Cooling air
- Turbulence models and alternative computational methods
- What experiments are needed?
- Absolute drag accuracy
  - What is current state of the art?
  - How much better than in 1998?
- Drag delta capability
  - Geometry changes affecting drag
  - Magnitude of drag change that can be discerned
  - Current capability/understanding?

Ames Research Center

Money

- Never enough for researchers
  - What are the areas that need to be addressed?
  - Other than DOE, what are the appropriate funding agencies/mechanisms?
- What payback do operators need to justify investing in aero improvements?
  - What productivity hits are allowable?
  - How much effort goes into aero improvements at OEMs? Does it "pay"?
- Are current and projected fuel costs high enough to raise priority of aerodynamic drag?

Overview of Michelin Research on Splash, Spray, and Aerodynamics

Ralph Hulseman

Michelin Americas Research and Development Corporation

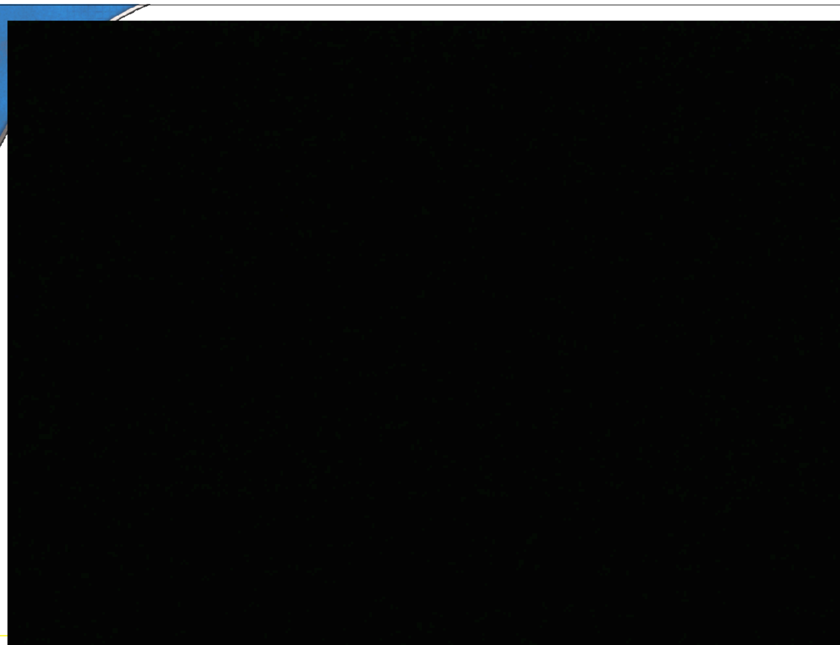
12 May 2005

MICHELIN
A better way forward

Anti-splash Feature on the Tire

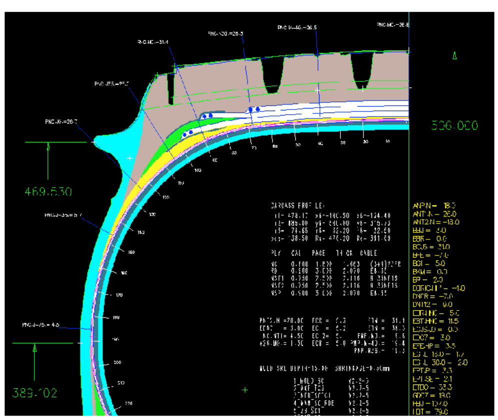
“Chine”

MICHELIN
A better way forward



Anti-Splash

- Objective:
  - Redirect water ejected from tire contact patch
  - Maintain all other types of tire performance



Technical Results Summary

- One tire size studied:
  - Up to 4x reduction in splash height
  - Large improvement of visibility for vehicle passing the truck creating a splash.
- Largest improvement observed when fitted to all axles, but, relative importance by axle position and vehicle type is not well understood.
- +5% manufacturing cost increase per tire.
- No major technical barriers encountered but experience is limited to one tire size (recapping, endurance, interference of duals, manufacturing)
- First size developed by trial and error. Design algorithms and simulation tools are needed to optimize for various tire sizes and vehicle configurations.
- Interactions with vehicle aerodynamics and spray formation are unknown.

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Heavy Truck Spray

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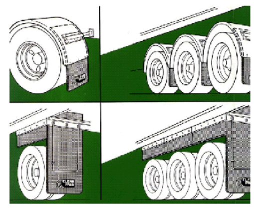
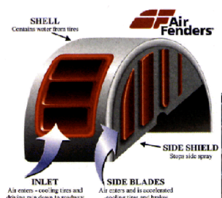
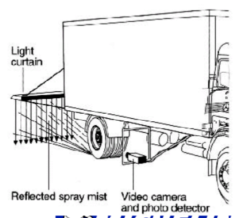
Anti Spray Devices & Test



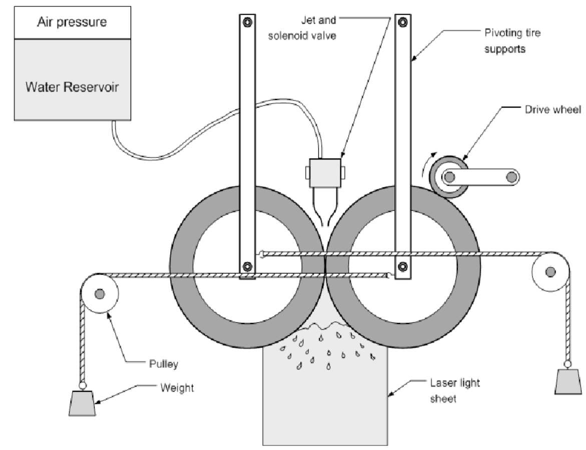




Mythology of Tires and Spray

- Some comments from the trucking industry:
  - "All the spray comes from the grooves in a rib tire"
  - "A block tire is worse than a rib tire"
  - "Super singles are better than duals"
  - "Nothing can be done with tires to reduce spray"
- However:
  - No studies of the physics of creation of spray by the tire are known.
    - Michelin / USC study underway
  - Tires have a measurable effect on vehicle aerodynamics
    - Michelin / Georgia Tech study.

work with USC



MICHELIN
A better way forward

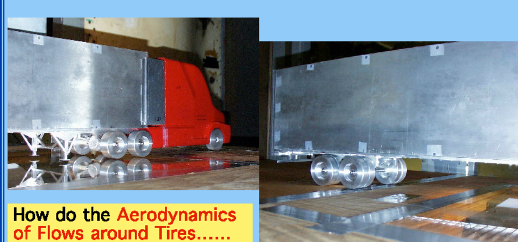
MICHELIN

Quantification of Tire Aerodynamics on Overall Heavy Truck Aerodynamics

by

Robert J. Englar, Georgia Tech Research Institute
Ibrahim M. Janajreh, PhD, Michelin Americas R&D Corp.

Georgia Tech Research Institute



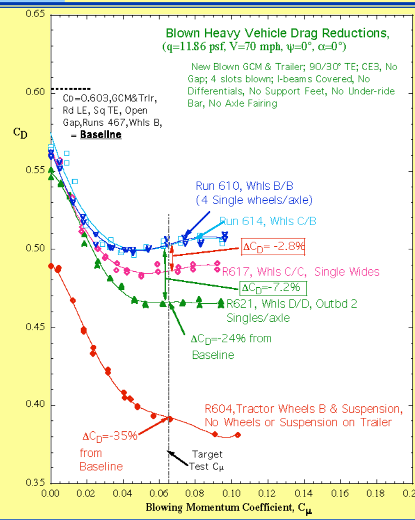
How do the Aerodynamics of Flows around Tires......

...and Under-body Flows affect the...

...Total Aerodynamics of Advanced Heavy Vehicles?

SAE 2004-01-2695

Wind Tunnel Results: Effect of Wheel Type on Blown Pneumatic Heavy Vehicle Drag



- Tire Blockage ahead of the Blown Trailing Edge Increases C_D
- Reduced Tire Thickness Reduces Blockage & Drag since Tire Wake is less
- Originally Postulated 1% Drag Reduction due to Wheels/Tires Appears Very Feasible
- Best Configuration (lowest C_D) is Trailer Wheels OFF (but not too practical) = No Wake

[$C\mu$ is Blowing Jet Momentum Coefficient; $C\mu$= Non-dimensional Jet Velocity x Mass Flow]

Questions?

Issues Summary

- Devices aren't on the road
  - Long history of studying devices
  - Need engineering/marketing for immediate impact

- Data isn't readily available
  - Intellectual property.....CRADA?
  - Literature survey
  - What is acceptable? necessary?
    - Absolute vs. % drag reduction
    - Wind tunnel conditions
    - Under hood considerations
    - 1/10th model w/ 40 devices: balance measurements

1

Issues Summary

- Industry disconnect
  - Where are the trailer people?
  - What are the operational restrictions that limit device use?
    - Brake light visibility w/ base flaps?
    - Restricted access to trailer
  - What has been tried? Was it worth it?
  - Why aren't systems integrated?
  - When will fuel prices force the issue?
  - Industry education

2

Issues Summary

➢Funding

- Priorities.....
- CRADA, DOE money generally goes to the labs, IP can be protected
- DOT may have interest in splash and spray
- OEM's and tire manufacturers don't get credit for reducing fuel consumption from EPA
- EPA – Smartway? Program to give credit

3

Path Forward

Heavy Vehicle Aerodynamic Drag
DOE Consortium Working Group Meeting

Rose McCallen

Lawrence Livermore National Laboratory

May 12, 2005

FY06 plans address issues and push into new areas

Get technology on the road
- Working with manufacturers/fleet – DOE Industry Consortium
- Full-scale testing – NRC Canada

System integration
- Reduction in fuel use
- Enhanced safety

engine cooling

Computational modeling that adequately captures reality
- Model scale and fidelity
- Multi-physics
- Operational environment

brake cooling

New areas
- Splash & spray, brake cooling, underhood
- Railcars

Funding
- Government teaming & leveraging funds

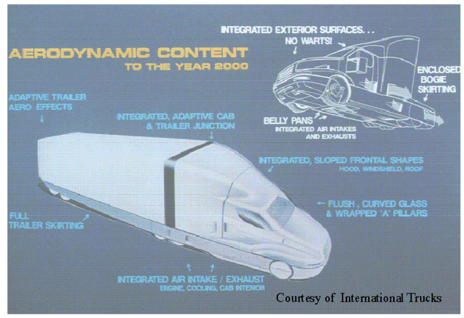
System integration for enhanced safety and performance WHILE reducing aero drag

Reduction in fuel use

- **Underhood**
- **Underbody**
- **Wheel aero (duals vs. singles)**
- **Mirrors, fenders, etc.**

Enhanced safety

- **Vehicle stability – wind loads**
- **Stopping distance – brake cooling**
- **Splash & spray**



Windload Stability: Overturning is countered by weight, dependent on roadway, and sensitive to wind gusts

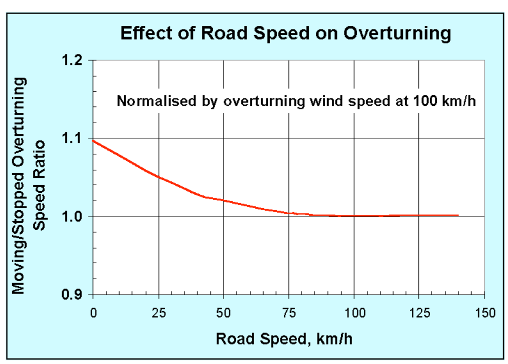
Quasi-static analysis provides order-of-magnitude results

Overturning wind speed, m/s

$$V_o \; ? \sqrt{\left(\frac{2}{?}\right)\left(\frac{yW}{C_R A_S h}\right)}$$

- y is track half-width
- C_R is aero rolling moment coefficient at 90° yaw
  - Conservative assumption is $C_R = 1.0$ at 90°
- W is weight in Newtons
- A_S is side area
- h is total height

Overturning wind decreases with forward speed



NRC · CNRC

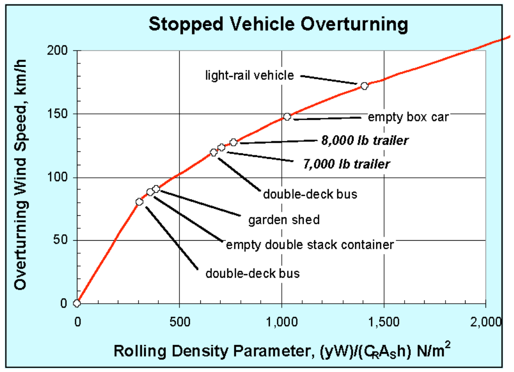
Overturning speed depends on rolling density

Turnover speed

8,000 lb trailer - 127 km/h (79 mph)

7,000 lb trailer - 119 km/h (74 mph)

The lower speed has a higher probability of occurrence



NRC · CNRC

Vehicle aerodynamics impact brake performance

Aerodynamics

Brakes operating at performance limits – cooling issues

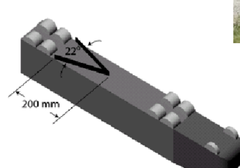
Aero drag reducing devices can make problem worse

- **Need more braking power**
- **Can redirect brake cooling flow**

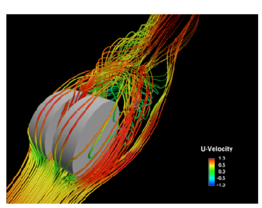
Challenges

Aerodynamics

- **Rotating wheels and tires**
- **Wheel wells**
- **Underbody**



Underbody wedge

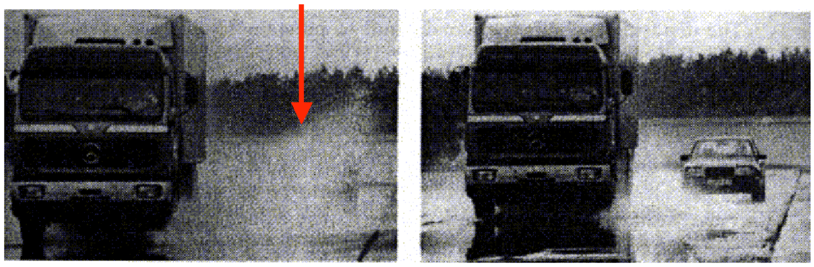


Aerodynamics of dual tires

Vehicle aerodynamics impact splash & spray

Car disappears behind spray

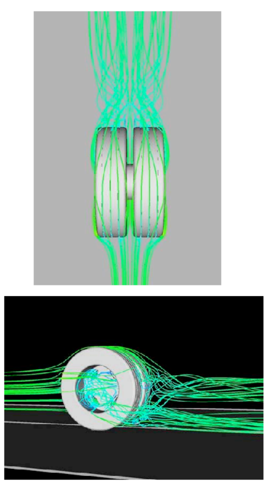
Fender fairings mitigate spray but do not prevent splash



1993 Annual Review of Fluid Mechanics
Photos Courtesy of Mercedes-Benz

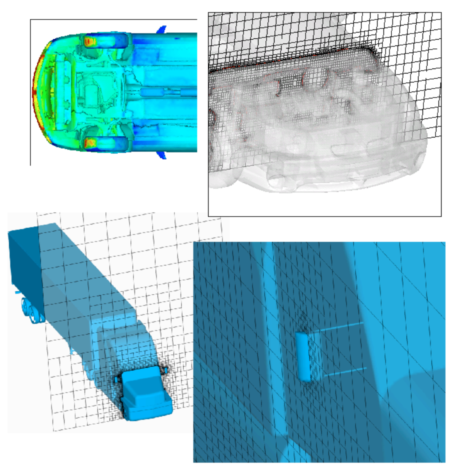
System integration requires high fidelity, multi-physics computational modeling

Tire/wheel details

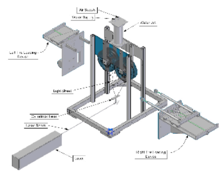


Immersed boundary method

Courtesy of DOE-ASC, Stanford University



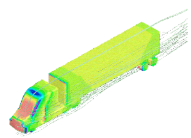
Integrated DOE/DOT effort = benefits for industry & nation



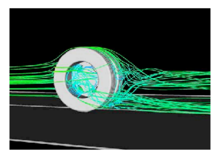
***Experiments** – DOE funding*
- Fundamental physical insight
- Realistic geometries & devices
- Simulation validation

Real-world application
- *Intelligent* device design
- Field testing

IMPROVE SAFETY



***Computations** – DOE funding*
- Investigate key physics
- System optimization
- Leverage national lab resources to advance the state-of-the-art



FY06 plans address issues and push into new areas

Get technology on the road

Working with manufacturers/fleet – DOE Industry Consortium

Full-scale testing – NRC Canada

System integration

Reduction in fuel use

Enhanced safety

engine cooling

Computational modeling that adequately captures reality

Model scale and fidelity

Multi-physics

Operational environment

brake cooling

New areas

Splash & spray, brake cooling, underhood

Railcars

Funding

Government teaming & leveraging funds

Discuss two separate and unrelated experimental programs

Briefly describe work on underhood flow management (proposed and awaiting funding)

Spend more time on preliminary results for the production of droplet sprays from tires

Aircraft Inspired Approaches to Management Of Cooling-Flow

James Bell
James Ross

NASA Ames Research Center

Separate flows for separate tasks

Experimental Program

Step 1

Use interior ducting to partition cooling air through radiator from cooling air for specific accessories

Provide for control of exit air flow for both of these functions

Step 2

Provide separate air passages for radiator cooling air and for accessories air

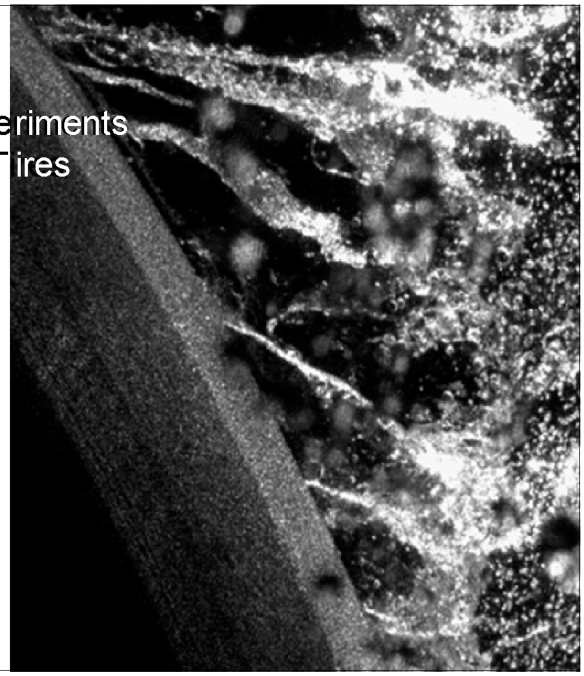
Diagnostics

Measure pressures throughout the engine compartment

Use temperature-sensitive paint for temperature measurement

Use DPIV-for velocity field information

Preliminary Experiments on Spray from Tires



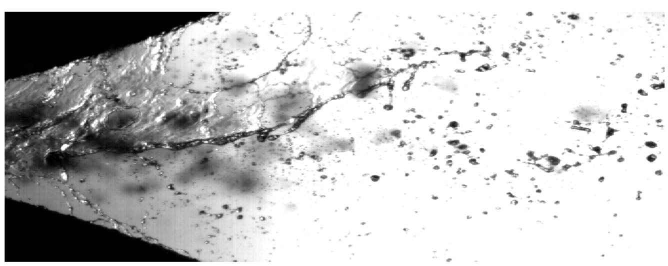
Fred Browand
Adam Fincham
Dennis Plocher
Tai Merzel
Charles Radovich

University of Southern California

Experiments on Spray from Tires

Water droplets often form as a result of the break-up of jets—or sheets—of fluid.

This is true in the case of tire-initiated spray also.



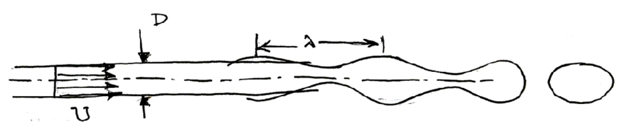
We must understand the physics of jet and sheet break-up.

Experiments on Spray from Tires

Rayleigh's problem: The solitary jet

Oscillations in the jet column form from random disturbances, and grow because the jet is unstable.

After sufficient disturbance growth, droplets are formed.



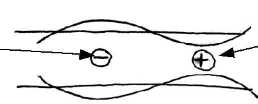
Unstable waves occupy: Wave speed = U, $\pi < \lambda/D < \infty$

Most unstable wave yields droplets of size: $d_{droplet} = 1.89\ D$

Experiments on Spray from Tires

The instability is driven by surface tension.

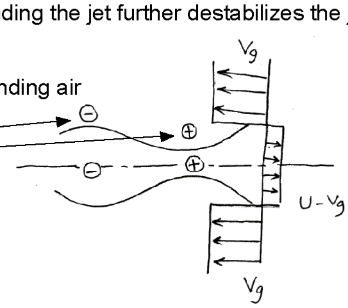
Radius larger here, pressure is less



Radius smaller here, pressure is greater

Addition of quiescent air surrounding the jet further destabilizes the jet.

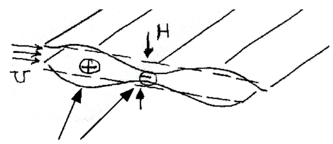
Riding with the wave, the surrounding air produces additional pressure differences.



Experiments on Spray from Tires

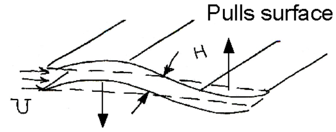
Sheets

Deformed sheets are stable when by themselves.



Surface tension creates pressure difference that drives fluid from crest to trough.

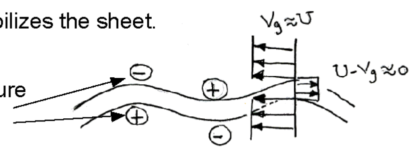
Surface tension Pulls surface up



Surface tension pulls surface down

… but a surrounding air mass destabilizes the sheet.

Sheet is driven laterally by the pressure differences in the surrounding air.



Experiments on Spray from Tires

Sheets

Sinuous disturbances are usually more unstable than varicose disturbances. When the amplitude of the wave is sufficiently large the sheet breaks up into droplets comparable in size to the local sheet thickness.

Since the sheet is driven unstable by the inertia of the surrounding air, the larger the inertia the more violent the wave growth will be.

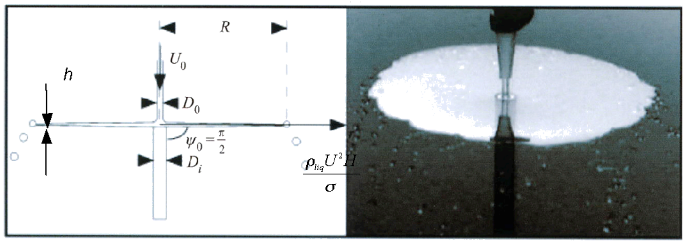
The effective inertia is measured—relative to (restorative) surface tension—by the Weber number.

$$We = \frac{\rho_{liq} U^2 H}{\sigma} \quad \left(or \quad \frac{\rho_{liq} U^2 D}{\sigma} \text{ for the jet}\right), \ \sigma \text{ is surface tension}$$

The larger the Weber number, the more violent the sheet (or jet) break-up will be, and the smaller the droplets will be.

Experiments on Spray from Tires

Examples: Clanet & Villermaux (JFM 2002)



Sheet thins as R grows: $\frac{R}{D_0} \approx \frac{We}{16}, \qquad \frac{h}{D_0} \approx \frac{10^{-1}}{We}$

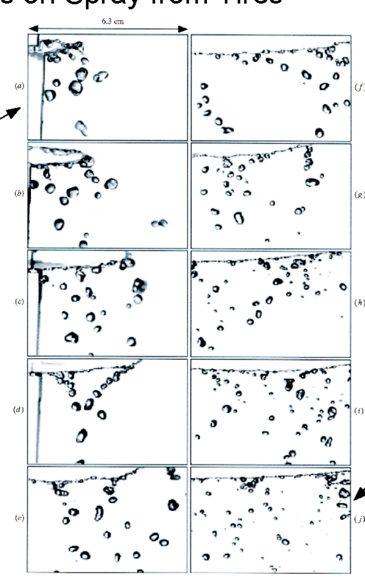
For *We = 1000*, $h/D_0 \approx 10^{-2}$

For D_0 *= 1 cm, droplet size* $\approx h \approx 100\ \mu m$

Experiments on Spray from Tires

Examples:
Clanet & Villermaux (JFM 2002)

We ≈ 150

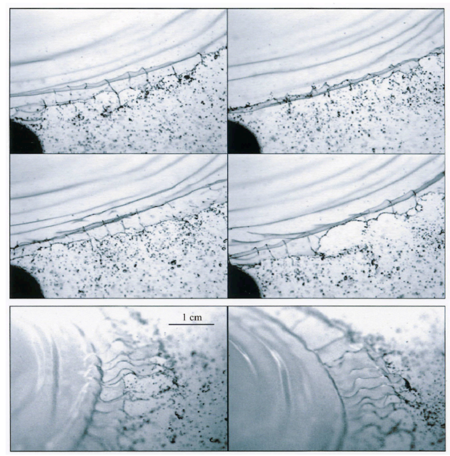


We ≈ 1000

Experiments on Spray from Tires

Examples:
Villermaux & Clanet (JFM 2002) Above We $\approx$ 1000, the K-H instability becomes dominant.

$$\frac{d_{droplet}}{D_0} \approx \frac{1}{(\frac{\rho_{air}}{\rho_{liq}})^{2/3}} \frac{1}{We} \approx \frac{90}{We}$$



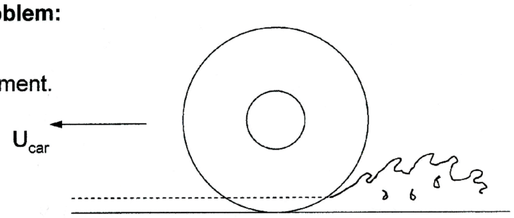
For $We \approx 40{,}000$, $d_{droplet}/D_0 \approx 0.0025$

For $D_0 = 1$ cm, $d_{droplet} \approx 25\ \mu m$

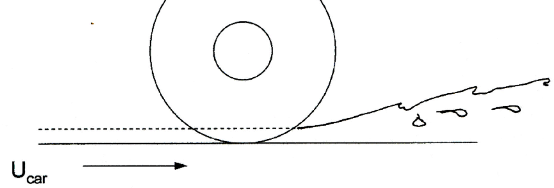
Experiments on Spray from Tires

Return to the tire problem:

Tire rolling on wet pavement.

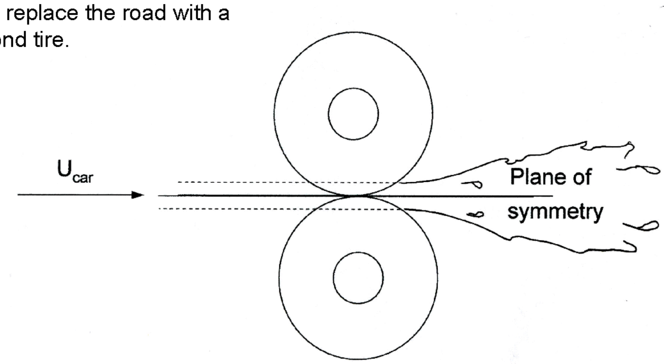


Riding with the car.

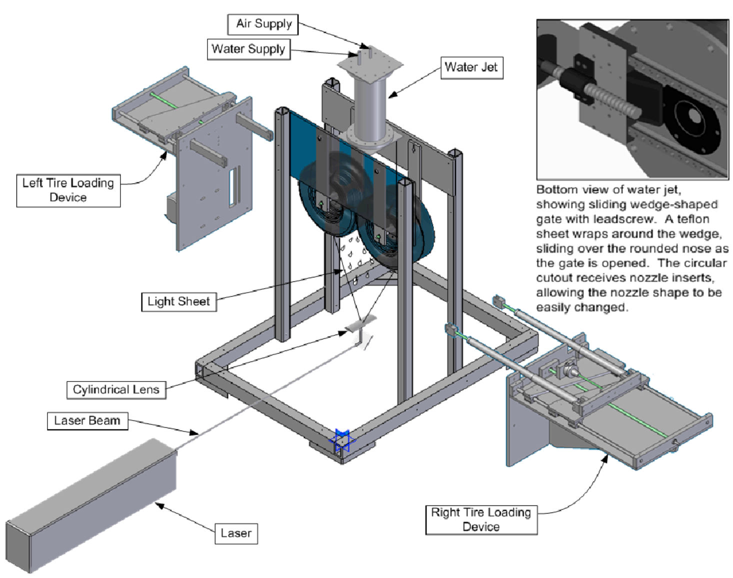


Experiments on Spray from Tires

Now replace the road with a second tire.



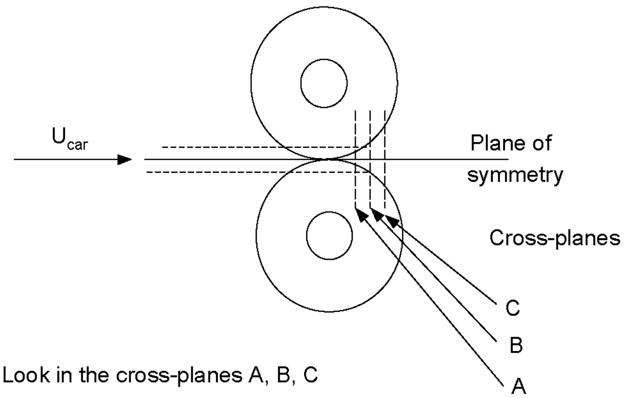
Experiments on Spray from Tires



Bottom view of water jet, showing sliding wedge-shaped gate with leadscrew. A teflon sheet wraps around the wedge, sliding over the rounded nose as the gate is opened. The circular cutout receives nozzle inserts, allowing the nozzle shape to be easily changed.

Experiments on Spray from Tires

How do “jets” and “sheets” fit the tire spray picture?

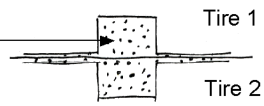


Look in the cross-planes A, B, C

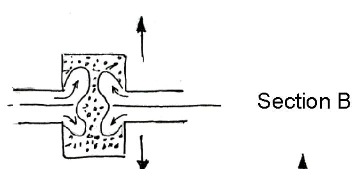
Experiments on Spray from Tires

How do “jets” and “sheets” fit the tire spray picture?

Water filling single, circumferential groove

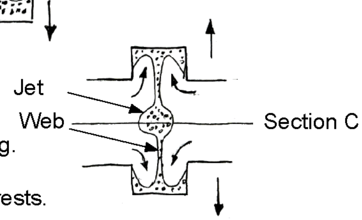


Tires move apart. Water is ejected from tread groove.



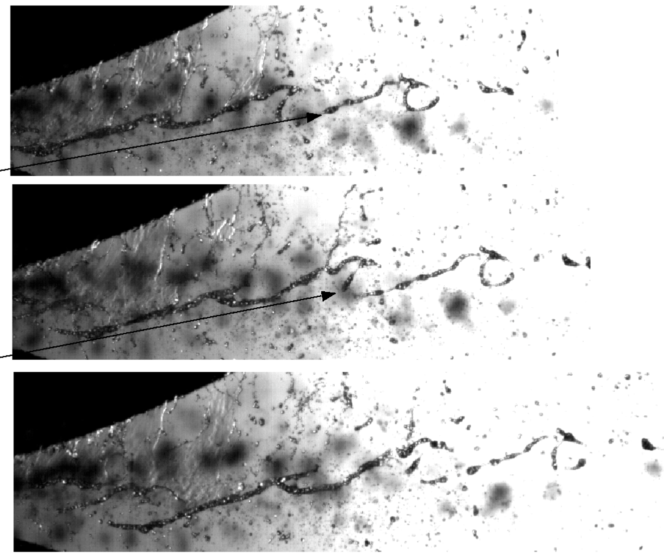
Central jet is unaffected by acceleration. It breaks up due to Rayleigh instability.

Web continually thins as a result of stretching. Waves on web travel in the downstream direction. Web appears to break between crests.



Experiments on Spray from Tires

Central jet instability



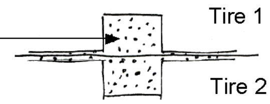
Droplets form from Rayleigh instability

Large-scale Kelvin-Helmholtz wave

Experiments on Spray from Tires

How do “jets” and “sheets” fit the tire spray picture?

Water filling single, circumferential groove



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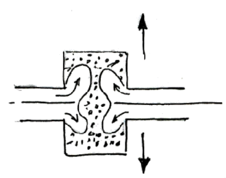

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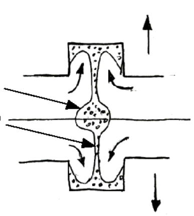
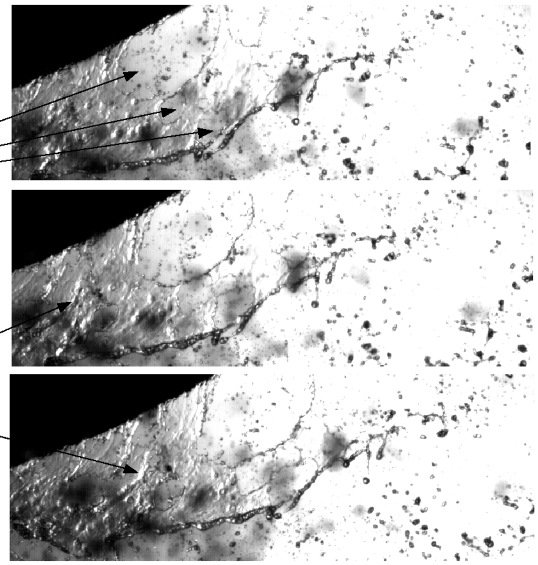


Experiments on Spray from Tires

Web break-up



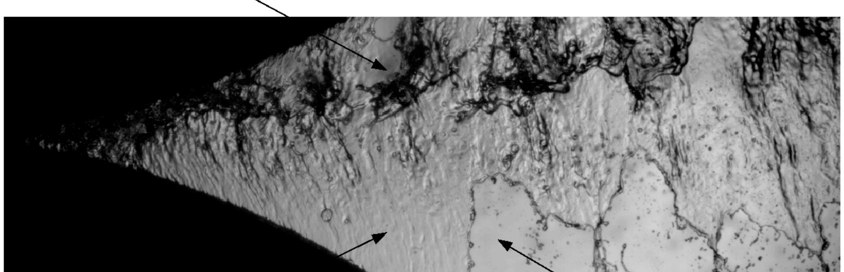
Breaks in web

Waves

Experiments on Spray from Tires

Another example, water delivery speed and tire speed approximately matched

Periodic structure, remnants of jet and attachments (ligaments) to tread



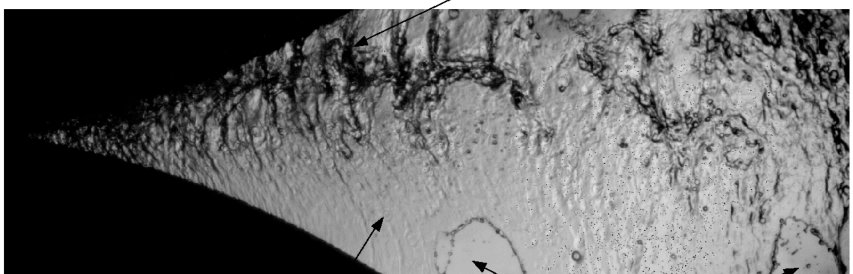
Thin web, less than 1mm in thickness

Breaks in web

Experiments on Spray from Tires

Another example, water delivery speed and tire speed approximately matched

Periodic structure, remnants of jet and attachments (ligaments) to tread



Thin web, less than 1mm in thickness

Breaks in web

Experiments on Spray from Tires

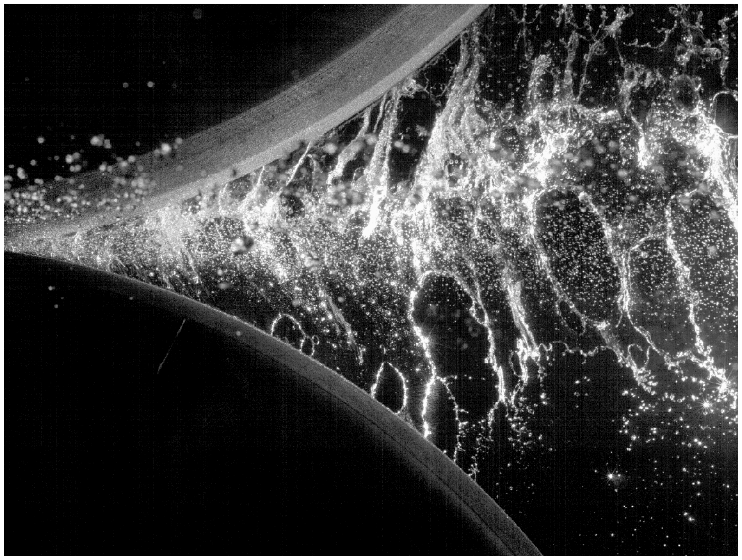
High-speed digital photography

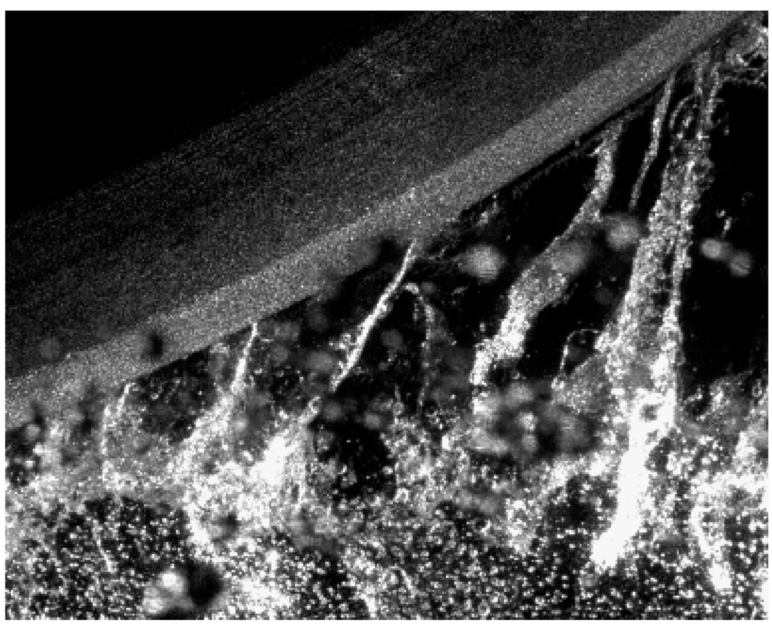
IDT digital camera from Integrated Design Tools, Inc.
1260x1024 pixels
Data storage, 1 gigabyte, expandable
Framing rate and exposure time separately variable
    currently operating with back-lighting at 2-4 μs exposure
    and framing of 1600-1700 fps with 250 mm x 70 mm
    field of view
    suitable for time history, and for Digital Particle Image Velocimetry (DPIV)

Laser sheet photography

2-tube Yag laser 150 mJoules per pulse
10 nanosecond pulse time
Sheet width variable—in this case ≈ 2-3 mm
Laser repetition rate ≈ 10 Hz
Operating modes
    single-tube, 10 Hz
    dual tube, 10 Hz, but variable time between pulses
    suitable for DPIV

Experiments on Spray from Tires





Experiments on Spray from Tires

Important non-dimensional parameters

$$Weber\ number\ = \frac{\rho U^2 H}{\sigma}$$

$$\frac{Jet\,speed}{Tire\,speed} = \frac{U_{jet}}{U_{tire}}$$

$$\frac{Jet\,volume\ flow}{Tire\text{"}swallowing\text{"}\,flow} = \frac{U_{jet} A_{jet}}{U_{tire} A_{tread}}$$

$$Reynolds\,number = \frac{UH}{\upsilon} >> 1\ \ and\ unimportant$$

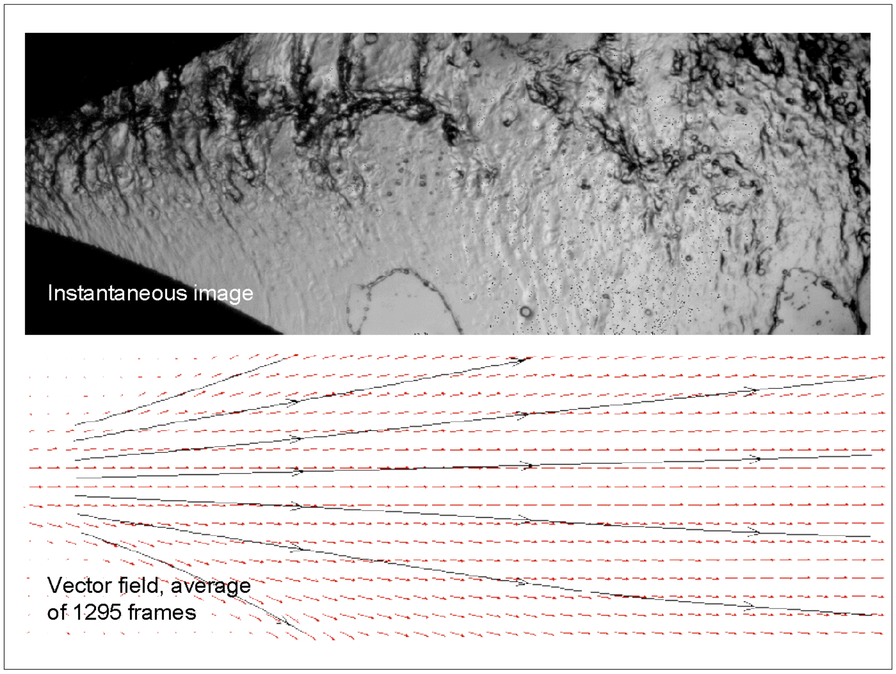
Experiments on Spray from Tires

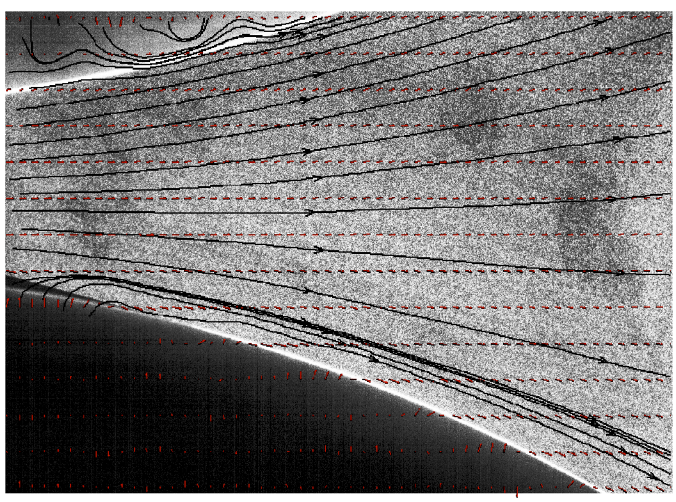
Where we are today

- <u>T</u>ire <u>S</u>pray <u>S</u>imulator or TSS completed (nearly)
- Demonstrated usefulness of TSS
  - Qualitative images using back-light and laser
  - Elucidate break-up mechanisms

Now the interesting (but hard) work begins

- Determine particles sizes and velocities


Instantaneous image
Vector field, average
of 1295 frames



Experiments on Spray from Tires

Improvements to apparatus needed

- Improve the water delivery
- Bring the experiment under computer control

Data acquisition

- Particle size distributions as a function of position in the field
- Velocity field, DPIV, for the various particle size categories

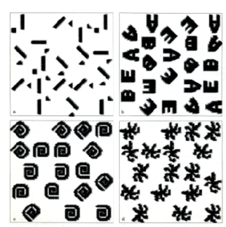
Requires local information on sizes (or scales)

- Image segmenting (c.f., “An algorithm for rapid image segmenting”, Sinkewitsch & Browand, *Exp in Fluids*, (about 1985)
- Wavelet transform (c.f., “The growth of large scales at defect sites in the plane mixing layer”, Dallard & Browand *JFM* 1993)

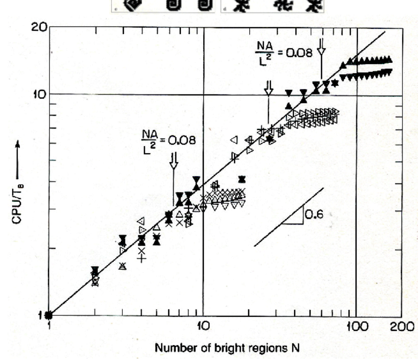
Experiments on Spray from Tires

Image segmenting

Raster scan technique picks out complex-shaped particles.



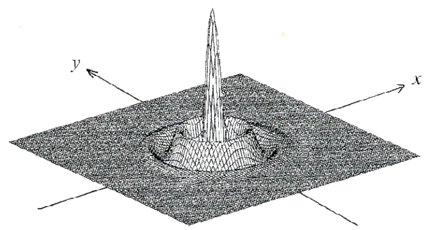
It is much faster than a sequential operation.



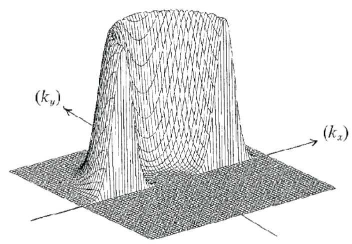
Experiments on Spray from Tires

Wavelet transform

Picks out spatial patterns, or scales, in space.



In wave number space, it is an arc, so we call it the Arc wavelet.



NRC·CNRC

From Discovery to Innovation...

NRC/NRCan Fuel Efficiency/Greenhouse Gas Program

J. Leuschen , K. R. Cooper

NRC Aerodynamics laboratory

Presented to DOE Heavy Vehicle Aerodynamics Meeting

May 12, 2005.

LLNL, Oakland, Ca.

National Research Council Canada Conseil national de recherches Canada

Canada

Goals

- To save fuel and reduce greenhouse gas emissions in heavy-duty trucks
- To use fuel savings as catalyst for change
- To use aerodynamic technology to provide reductions
- To successfully transfer new technology to industry
  - Wind tunnel development
  - On-road testing and demonstration
- Involve the trucking industry through their Provincial and National organisations

Resources

- $800,000.00 Canadian dollars over FY 2004-2007
- Approximately $400,000.00 for model and full-scale wind tunnel testing
- The remainder for technology transfer, including:
  - Engineering road tests
  - Fleet trials
  - Seminars/web site/trade shows

Partners

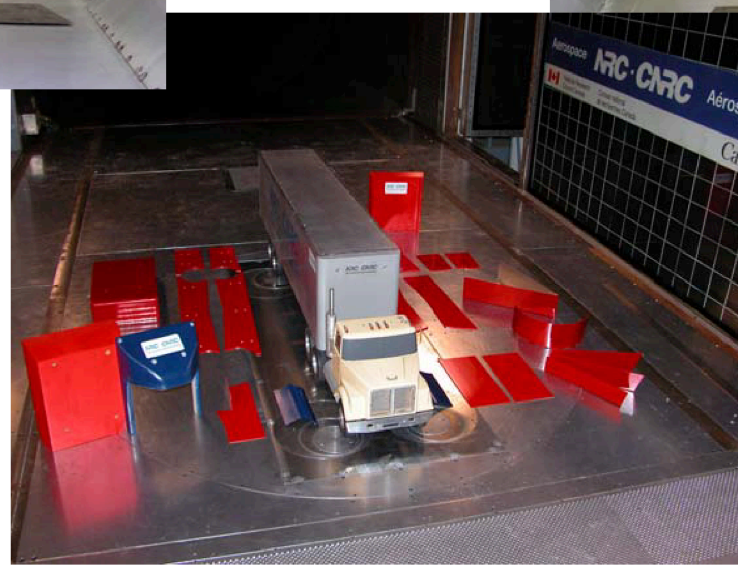
- ***Non-competitive, non-commercial program***
  - *Not intended to invent products*
  - *Designed to transfer technology to benefit of truckers & country*
- Funded by Natural Resources Canada
- Align effort with DOE program to lever investment
  - Test common hardware
  - Exchange wind tunnel and road data
  - Share hardware where possible
  - Interface with OEMs

Program Outline

- Model wind tunnel testing completed March 2005
- 1st-phase full-scale tunnel testing completed April 2005
- 2nd-phase full-scale tunnel testing in fall 2005
  - Need components for test
- Road and fleet trials 2006-2007
  - Need vehicles and hardware for test
    - Coast-down, fuel consumption
    - Fleet trials

Truck Fuel Saving Greenhouse Gas Reduction

Lets work together



NRC·CNRC

NRC·CNRC

From Discovery to Innovation...

Early Wind Tunnel Test Results from The NRC/NRCan Greenhouse Gas Program

J. Leuschen , K. R. Cooper

NRC Aerodynamics laboratory

Presented to DOE Heavy Vehicle Aerodynamics Meeting

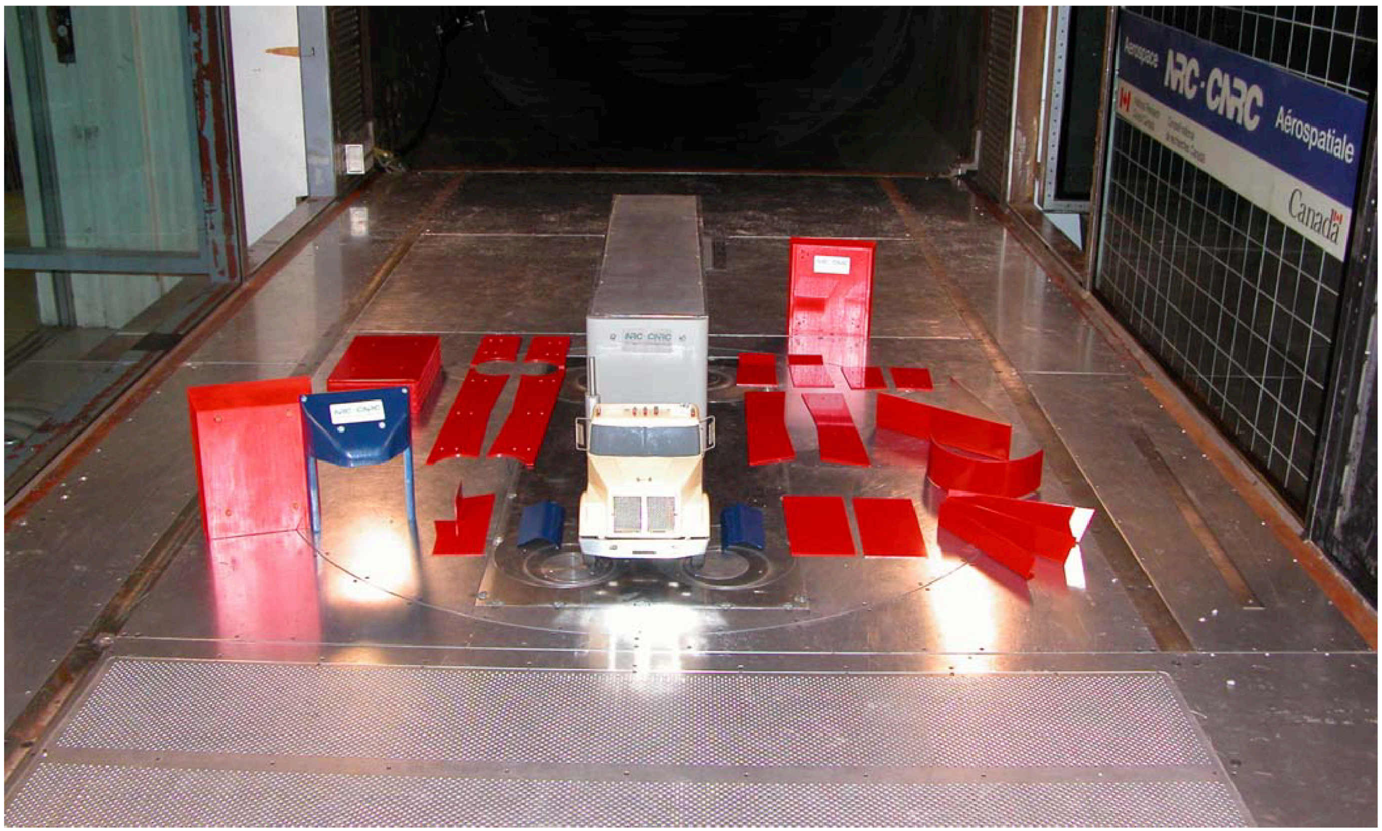
May 12, 2005.

LLNL, Oakland, Ca.

Model-Scale Development Program

- 1:10-scale highly detailed model
- Test speed of 75 m/s, $Re_W \approx 1.25 \times 10^6$
- Focussed on:
  - Boat-tail
  - Tractor/trailer gap treatments
  - Skirts
  - Under-trailer treatments

Model-Scale Development Program



NRC · CNRC

Model-Scale Development Program

- Best combination – skirts, boat-tail, longer cab extenders

Model-Scale Development Program

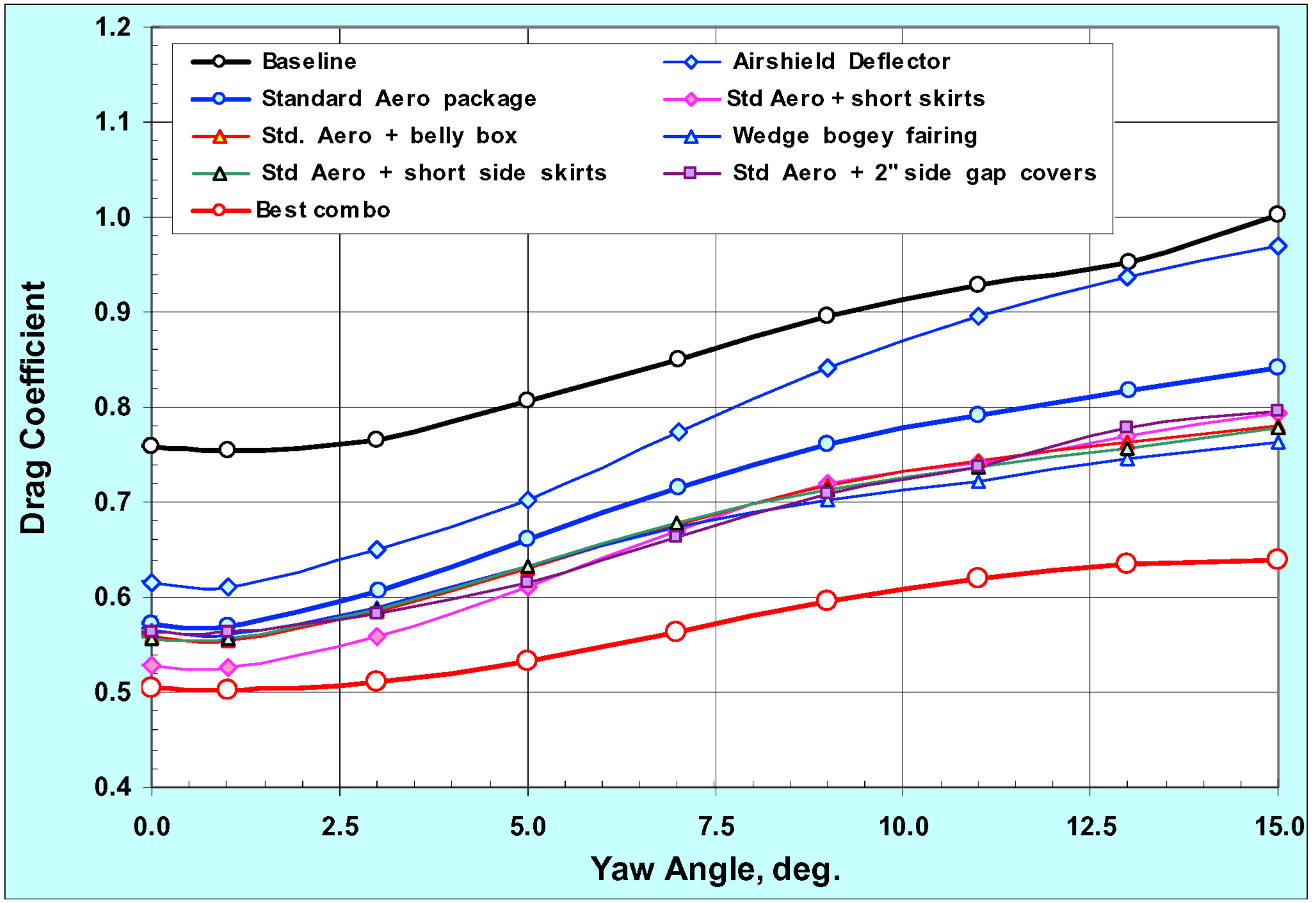
Wedge bogie fairing

Vortex stabilizer

Belly box

NRC · CNRC

Summary of Model-Scale Results



Summary of Model-Scale Results

Configuration	C_D *bar* 55 mph	C_D *bar* 65 mph	ΔC_D *bar* 55 mph	ΔC_D *bar* 65 mph	Fuel Savings [gal/100mi@65]
Std Aero Baseline	0.661	0.640	-	-	-
Std Aero + Boat-Tail	0.613	0.591	0.048	0.048	1.02
Std Aero + Long Skirts	0.618	0.601	0.043	0.038	0.81
Std Aero + Short Skirts	0.634	0.615	0.028	0.024	0.52
Std Aero + 2" Extenders	0.624	0.607	0.037	0.033	0.70
Std Aero + Belly box	0.631	0.613	0.030	0.027	0.57
Long Wedge Bogey Fairing	0.633	0.616	0.028	0.024	0.51
Best Combination	**0.540**	**0.529**	**0.121**	**0.111**	**2.35**

First Full-Scale Demonstration Program

- Full scale tractor and 40’ trailer
- Test speed of 65 MPH
- Focussed on verifying best 1/10th scale configuration:
  - Boat-tail
  - Tractor/trailer gap treatments
  - Skirts

Full-Scale Best Combination

NRC · CNRC

Full-Scale Test Items

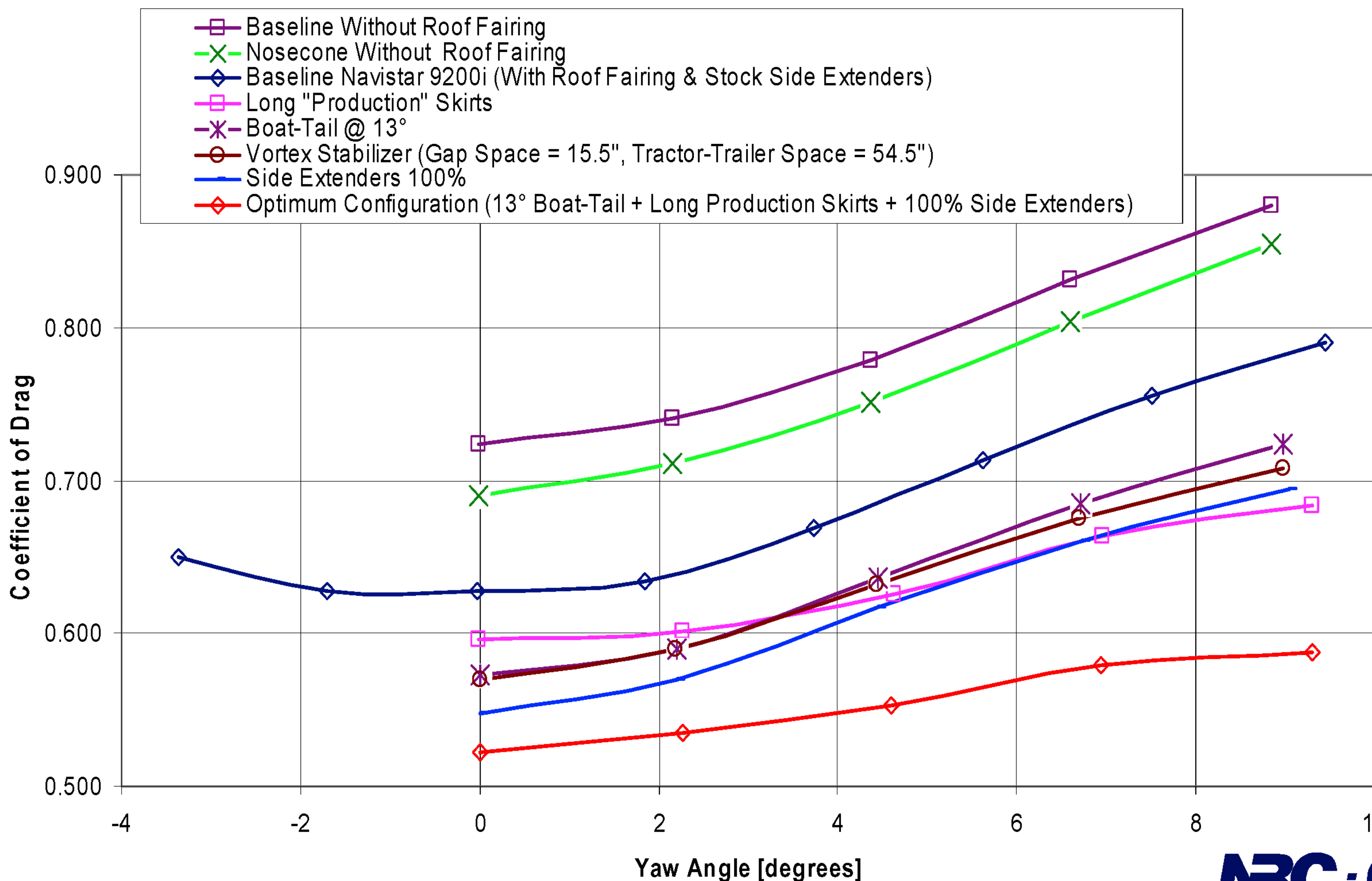
Norcan Boat-Tail

Side Extenders

Trailer Skirts

NRC·CNRC

Summary of Full-Scale Results



NRC · CNRC

Summary of Full-Scale Results

Configuration	C_D bar 55 mph	C_D bar 65 mph	ΔC_D bar 55 mph	ΔC_D bar 65 mph	Fuel Savings gal/100mi@65
Non-Aero Baseline	0.812	0.791	-	-	-
Nosecone	0.784	0.762	0.029	0.029	0.62
Std Aero Baseline	0.716	0.695	0.096	0.097	2.05
Std Aero + Boat-Tail	0.662	0.643	0.054	0.052	1.10
Std Aero + Long Skirts	0.659	0.643	0.057	0.052	1.11
Std Aero + Side Extenders	0.640	0.621	0.077	0.073	1.56
Vortex Stabilizer	0.656	0.638	0.060	0.057	1.20
Best Combination	**0.580**	**0.567**	**0.136**	**0.128**	**2.71**

Conclusions

- Wind tunnel test allowed many prototype and production items to be tested quickly
- Most promising devices were skirts, boat-tails and side extenders
- Vortex stabilizer and underbody fairings aren't as effective
- While conclusions drawn from full- or 10^{th}-scale data were similar, full-scale tests are felt to be more convincing

Follow-Up

- 2nd wind tunnel test in 2005 to test other prototypes (Freightwings, Aeroworks, Air Tabs?)
- CFD simulations to extrapolate results to other trailer configurations and lengths
- Fleet Trials / Outreach

Path Forward: A Summary

- Continue to improve computations
  - Pursue advanced meshing strategies
    - Embedded surfaces
  - Use higher fidelity geometries
    - Detailed underbody and engine compartment
  - More realistic environments
    - Rotating tires
    - Moving ground plane
- Looking at underhood thermal control
  - Using aircraft engines for design inspiration
    - Ducting the interior to partition the flow
    - Control the exit air
    - Propose an experimental program

Path Forward: A Summary

- Improving international cooperation
  - Canadian effort is driven by greenhouse gas emissions
  - Working to align effort with DOE programs
    - Test common hardware
    - Share data
    - Share hardware where possible
    - Combination of model and full-scale tests (road and wind tunnel)
    - Best drag improvement with skirts, base flaps, and side extenders
- Address operational issues
  - Need to work with fleets

Path Forward: A Summary

- Brake cooling and splash and spray: simulations
  - Ultimate goal is an integrated splay and spray model
  - Challenges need to be addressed
    - Complex geometries
    - Unsteady flow
    - Need models for droplet breakup and transport
    - Need validation data
  - Team advantages
    - Computational facilities
    - Expertise
- Splash and spray: experiments
  - Nearly completed work with the tire spray simulator
  - Examining the fundamental physics for jet breakup and droplet formation
  - Need to extract velocity fields and particle sizes
- Splash and spray leads to corrosion and icing

Viewgraphs from May 13, 2005 meeting in order of presentation

Review of Key Items

- TMA bullet items:
  - Mirror Design/Configuration
  - Trailer Gap/Side/Wake Treatments (gap closure, side enclosure, trailer wake
  - Trailer Aero/Gap Enclosure/Gap Flow Control
  - Vehicle Underside Airflow/Thermal Control
  - TMA Truck Test Day -- Opportunity to demonstrate technologies? Do we have to wait for final report to see the results?!?!?
- OEMs have a need to sanitize data, but they must do it such that discoveries are shared and resources are known
- Over-arching critique/comment

  We are too isolated. We need to work together. In order to grow and improve, we need to share and not have everyone "re-inventing the wheel."

1

Review of Key Items

- We should report ΔC_D's instead of percent drag reduction.
- Need to consider underhood/underbody, open radiator, etc. especially as we move to higher fidelity models.
  - Do we have enough information (BC's, validation data, etc.) to make CFD including these complications believable?
- End-user interaction needs to be "stepped up." Put users "in the middle" so that the people at the R&D end are aware of access, maintenance and liability issues.
  - Industry must offer some guidance.
  - As a federal research agency, we have an obligation to show what *can* be done, not just what is feasible in the near-term.
- Have we considered every possible device? Every feasible device?
- Sid likes Hula skirts (non-monolithic skirts)

2

Review of Key Items

- WE NEED TO GET OUR DEVICES ON THE ROAD
  - We've done enough research to make this a reality. It's time to enter the development cycle and get things like skirts, splitter plates, etc. manufactured and used. We've got NorCan onboard. We need more.
- Product Engineering
- "Honest Broker" ?
- Marketing, marketing, marketing, marketing.

3

Open Questions

4

Issues involving add-ons in general and base flaps in particular

It's time for over-the-road, fleet operation testing.

Tractor manufacturers have not been very supportive. They will always resist change.

The business is entirely customer driven, so deal directly with the operators, such as US Xpress/Wall-Mart?/UPS?/Schneider?

Can we offer funding support or other inducements? Point out that they could use flaps for fuel-friendly, green-house gas-friendly advertising.

Should we have something waiting in the wings if oil production falls precipitously (Ray Smith's comment)?

What about using the top flap as a brake?

Alec Wong wondered how well the two side flaps alone would work. Good selling point, he said. Should we ask Kevin to test it?

Hybrid truck

Low drag has an even larger payoff since less aerodynamic drag means more kinetic energy recovery with use of motor braking.

Δ(KE) ~ MVdV. It is not so clear whether small speed changes at high speed (truck on highway) would add to more saving than large speed changes at low speed (around-town in traffic).

Quantify savings for hybrid truck for different driving cycles (EPA-Highway or EPA-Town or other). See paper presented at SAE World Congress in April 2005 by Gino Sovran and Dwight Blase (sp??).

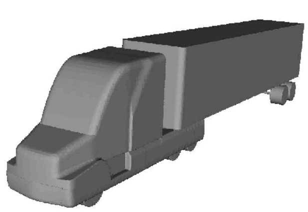
Evaluation of Drag Reduction Devices Using Modeling and Simulation

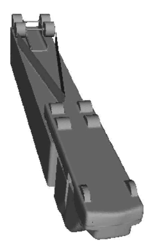
Jason Ortega

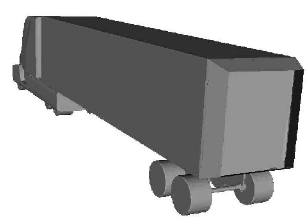
Lawrence Livermore National Laboratory

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48. UCRL-PRES-212223.

Drag Reduction Devices to be Tested


Baseline


Long Wedge Skirt

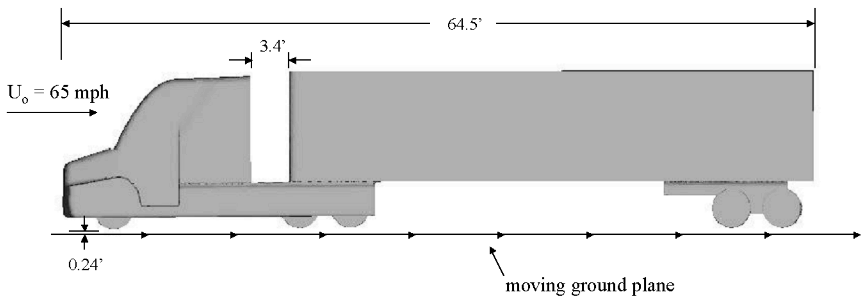

Base Flaps

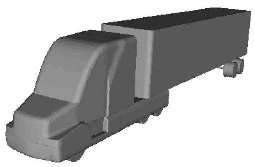
Questions to be Addressed by Numerical Simulations

- How does flow unsteadiness affect device performance?
- How do rotating wheels influence the performance of the base flaps?
- Will the wedge skirt function at realistic Reynolds numbers with more realistic boundary conditions?
- How do the devices modify the flow field about the GCM?
- Can we further optimize the drag reduction devices to be more effective and less intrusive?

Computational Setup

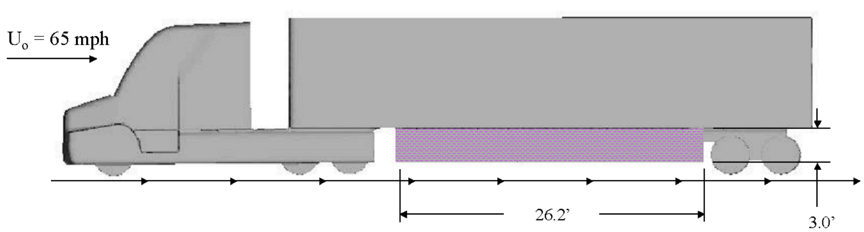
Full-Scale Baseline GCM

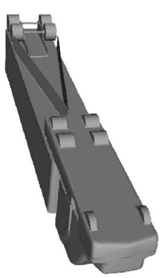




- Full-scale GCM geometry
- $Re_w = U_o w/\nu = 5.02\times10^6$
- Moving ground plane beneath vehicle
- Grid resolution: 5.6×10^6 elements
- STAR-CD CFD code
- Steady RANS simulation
- $k\omega$-SST turbulence model with wall functions

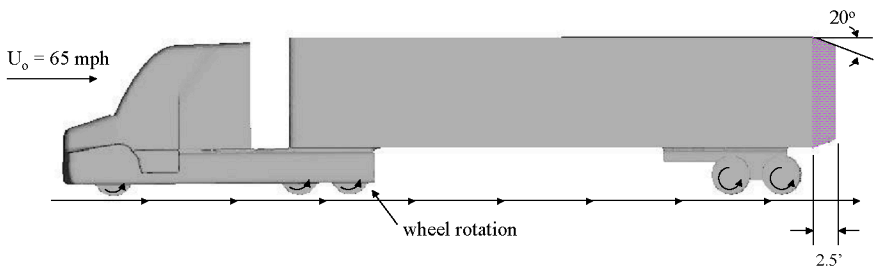
Baseline GCM with Long Wedge Skirt

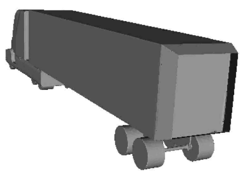




- Grid resolution: 5.6×10^6 elements
- Steady RANS simulation
- $k\omega$-SST turbulence model with wall functions

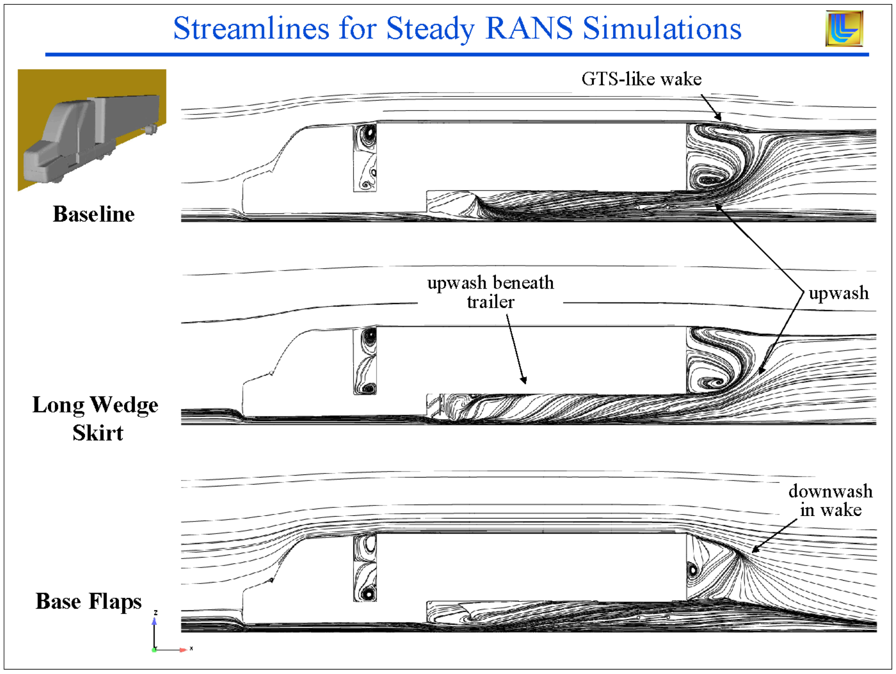
Baseline GCM with Base Flaps

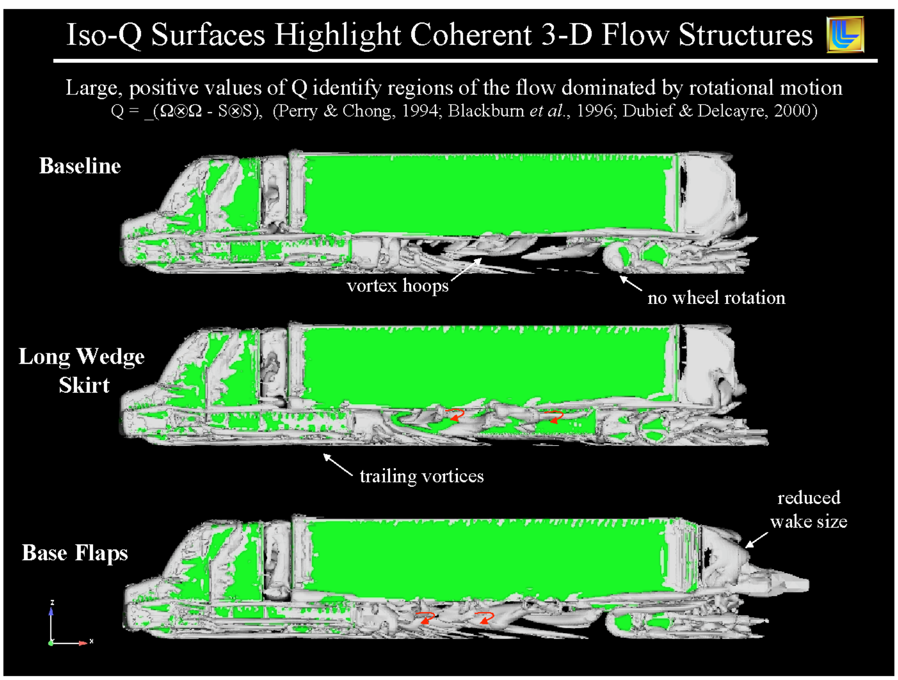




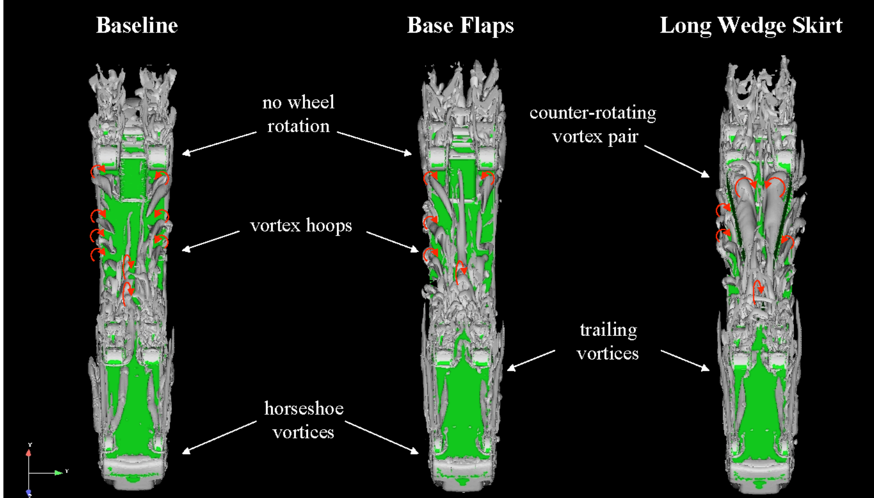
- Grid resolution: 1.5×10^6 (unsteady) and 6.0×10^6 (steady) elements
- Unsteady RANS simulations with and without wheel rotation
- kω-SST turbulence model with wall functions

Results


Streamlines for Steady RANS Simulations
GTS-like wake
Baseline
upwash beneath
trailer
upwash
Long Wedge
Skirt
downwash
in wake
Base Flaps

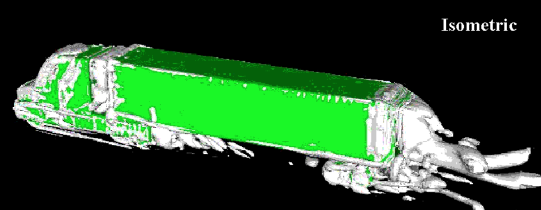

Iso-Q Surfaces Highlight Coherent 3-D Flow Structures
Large, positive values of Q identify regions of the flow dominated by rotational motion
Q = _(Ω⊗Ω - S⊗S), (Perry & Chong, 1994; Blackburn et al., 1996; Dubief & Delcayre, 2000)
Baseline
vortex hoops
no wheel rotation
Long Wedge
Skirt
trailing vortices
reduced
wake size
Base Flaps

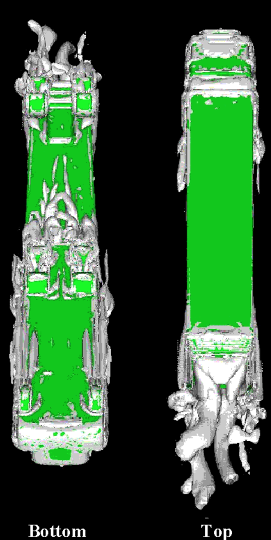
Iso-Q Surfaces Highlight Coherent 3-D Flow Structures



Iso-Q Surfaces for Unsteady RANS Simulations

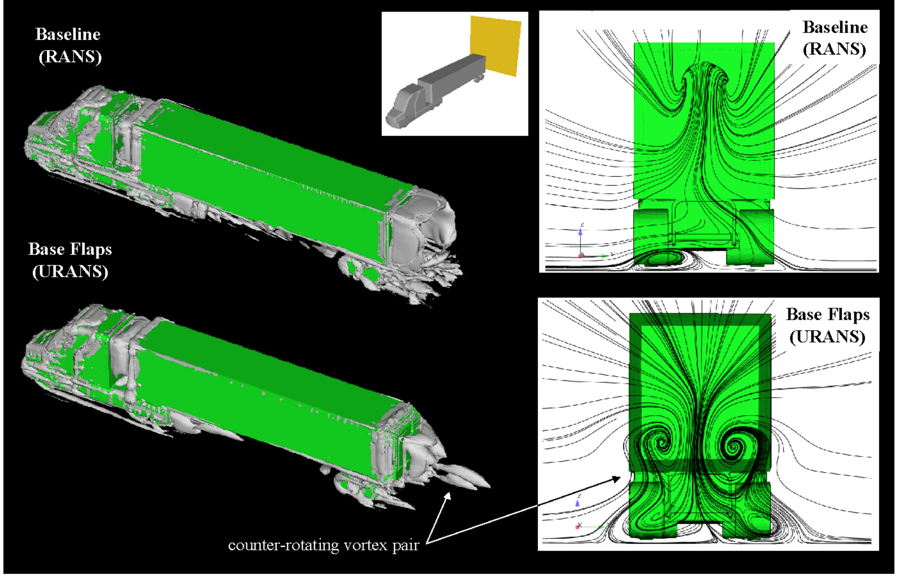
- Base flaps with wheel rotation
- Grid resolution: 1.5×10^6 elements
- $k\omega$–SST turbulence model with wall functions



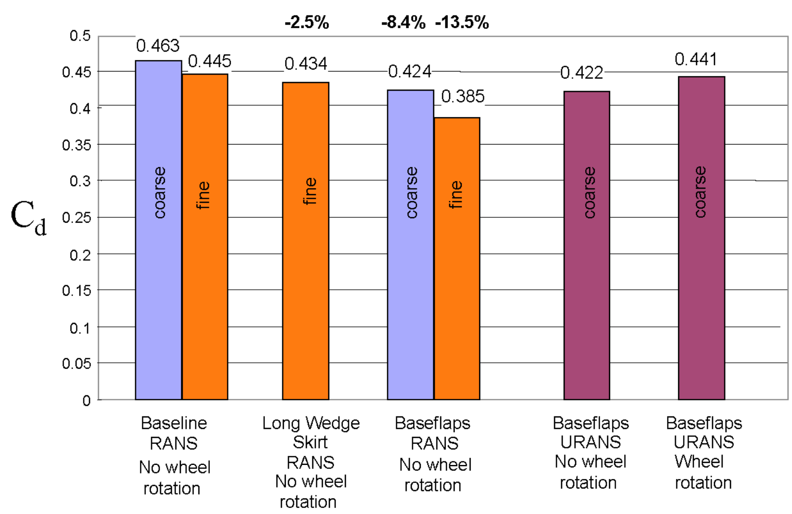


- URANS highlights the complex, unsteady, 3-D nature of the flowfield about the GCM
- Significant flow unsteadiness on the GCM underside from the tractor base, tractor wheels, and trailer wheels
- Large scale flow structures present in the GCM wake

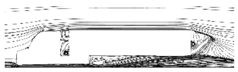
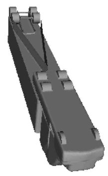
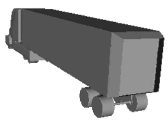
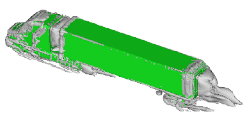
Base Flaps Modify the Flow field by Generating a Counter-Rotating Vortex Pair in the GCM Wake



Influence of Drag Reduction Devices and Wheel Rotation on C_d

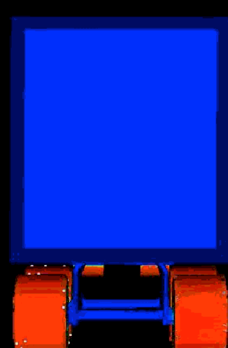


Summary

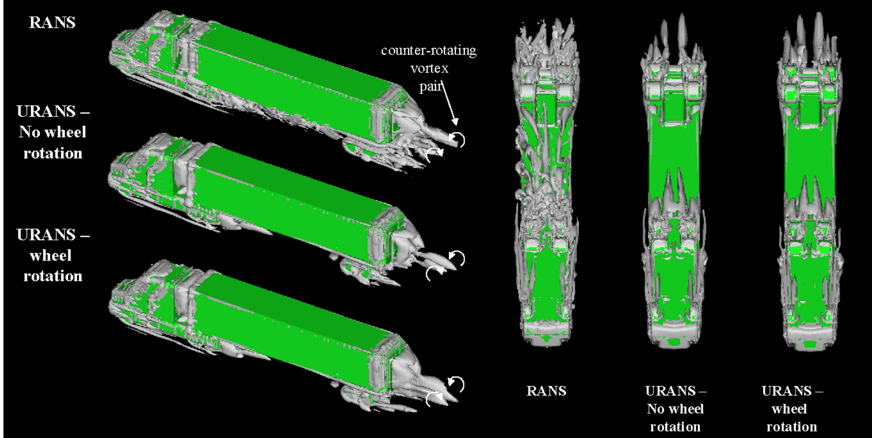





- How does flow unsteadiness affect device performance?
  - $C_{d\ RANS} \approx C_{d\ URANS}$ for the base flaps configuration at 0° yaw
- How do rotating wheels influence the performance of the base flaps?
  - $C_{d\ rotating} > C_{d\ non\text{-}rotating}$
- Will the wedge skirt function at realistic Reynolds numbers with more realistic boundary conditions?
  - $\Delta C_d/C_d \approx 2.5\%$ at 0° yaw
- How do the devices modify the flow field about the GCM?
  - Base flaps generate downwash and a counter-rotating vortex pair in the GCM wake
  - Long wedge skirt generates upwash beneath the trailer by means of a counter-rotating vortex pair
- Can we further optimize the drag reduction devices to be more effective and less intrusive?
- Steady RANS simulations are inadequate to fully understand the complex, 3-D evolution of the flow field about the GCM

Time-Averaged URANS: Base Flaps with Wheel Rotation



Iso-Q Surfaces: RANS & Time-Averaged URANS

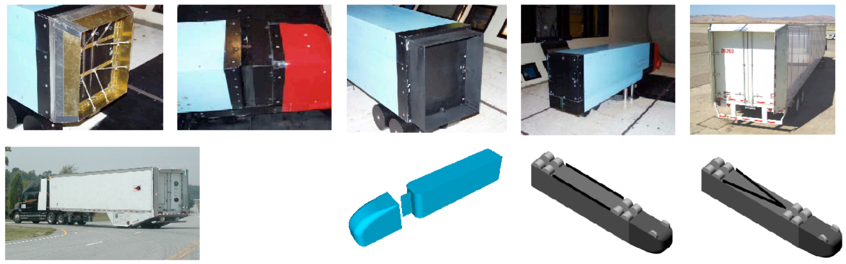


- Significant difference between the underside flow of the RANS results and the time-averaged URANS results
- All three base flaps cases demonstrate a counter-rotating vortex pair in the wake of the GCM
- Wheel rotation slightly changes the wake structure

Overview

- Motivation and Background
- Computational Setup
- Results
- Conclusions

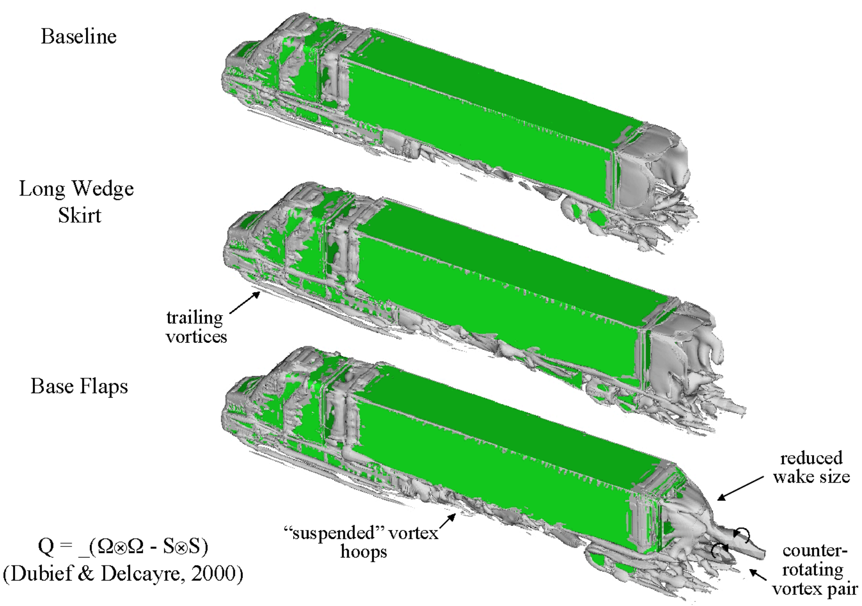
Devices Shown to Provide Drag Reduction



Percent change in wind-averaged drag coefficient/
Fuel Economy

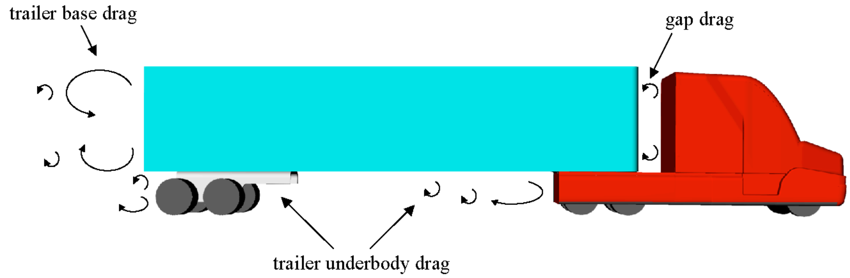
Device	NASA	USC	GTRI	LLNL
Side Extenders	37%	———	———	———
Gap Splitter Plate		n/a	———	———
Boattail Plates	13.7%	———	———	8.8%
Base Flaps	19.4% (20)	**~ 4.15% (13)**	———	16.4% (10)
Straight Side Skirts	6.5%	———	———	1.4%
Long Wedge Skirt	———	———	———	2.1%
Low Boy	11.8%	———	———	———
PHV	———	———	**~ 4-12%**	———

Iso-Q Surfaces for Steady RANS Simulations



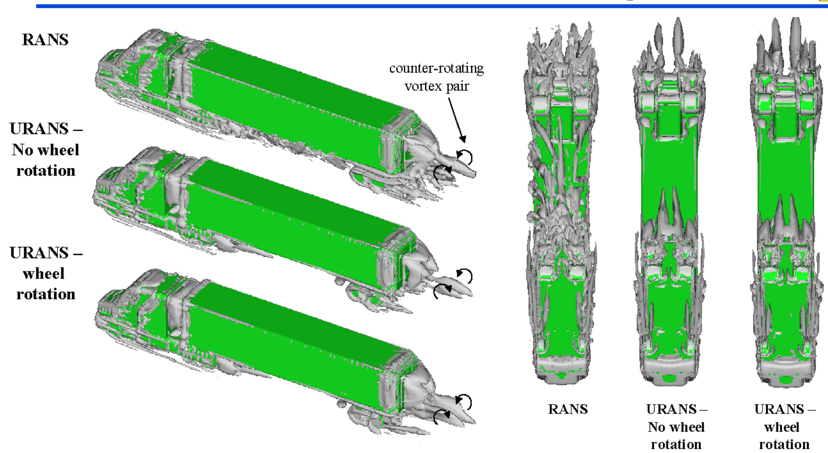
$Q = \_(\Omega\otimes\Omega - S\otimes S)$
(Dubief & Delcayre, 2000)

Major Sources of Aerodynamic Drag



- Cross-stream flow in the tractor/trailer gap
- Trailer underbody drag due to flow separation off of tractor underside and flow impingement on trailer wheels
- Separated flow off of the trailer base

Iso-Q Surfaces: RANS & Time-Averaged URANS



- Significant difference between the underside flow of the RANS results and the time-averaged URANS results
- All three base flaps cases demonstrate a counter-rotating vortex pair in the wake of the GCM
- Wheel rotation slightly changes the wake structure

Computational Simulation of Tractor-Trailer Gap Flow with Aerodynamic Devices

Paul J. Castellucci

Kambiz Salari

Heavy Vehicle Aerodynamic Drag: Working Group Meeting

May 13, 2005

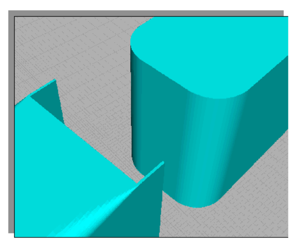
Lawrence Livermore National Laboratory

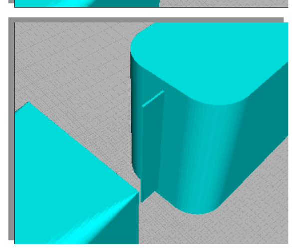
UCRL-PRES-212230

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

Gap Flow Simulations of the M-GTS are Chosen For Experimental Comparison

- **Simulations are performed with both tractor cab extenders and single trailer splitter plates (approx 20").**
- **Each device is tested at 6° yaw and non-dimensional gap lengths of 0.35 and 0.65 (approx 3' – 6').**
- **USC has compiled body force and PIV data of the Modified Ground Transportation System (M-GTS) at Reynolds number 340,000.**

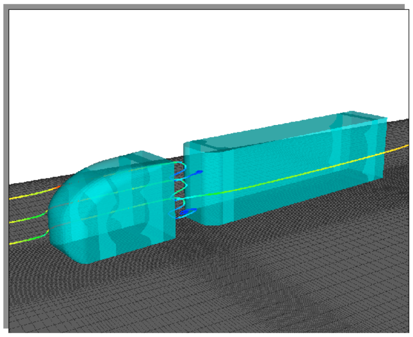




DOE 51305-2

Gap Flow Simulations of the M-GTS are Chosen For Experimental Comparison

- **Simulations are performed using NASA's OVERFLOW; a compressible, control-volume based, Navier-Stokes code using overset grids.**
- **Based on prior GTS simulations, all cases are run with Menter-SST steady RANS turbulence model.**
- **A moving ground plane boundary condition is employed to mimic experimental conditions.**

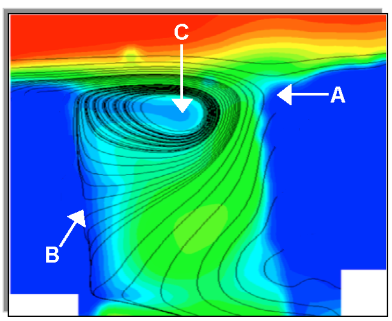


Baseline M-GTS at 6° yaw

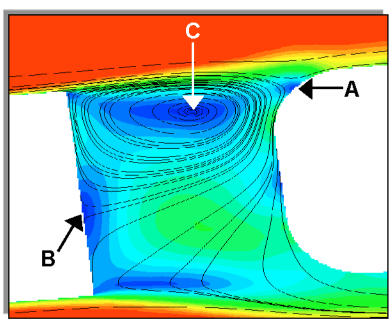
DOE 51305-3

Baseline Simulations Capture Qualitative Gap Flow Features

Baseline M-GTS Streamlines and Velocity Magnitude Contours



Experiment at 6° Yaw and 0.65 Gap (Browand)



Simulation at 6° Yaw and 0.65 Gap

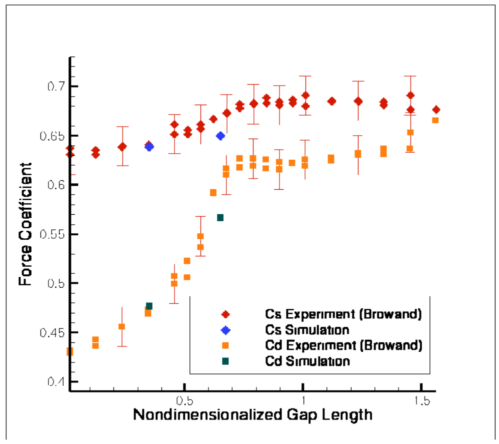
- **Stagnation points (A, B) and vortex core (C) are similar to PIV data.**
- **Flow velocities are comparable, yet consistently lower than experiment.**

DOE 51305-4

Baseline M-GTS Body Forces Compare Favorably to Experimental Data

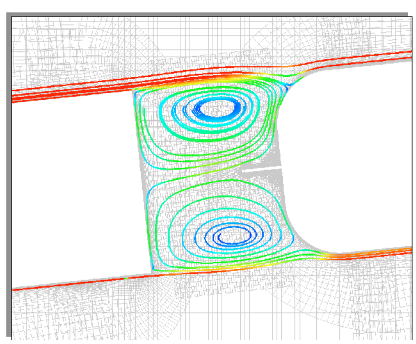
- Computed drag and side force coefficients are within experimental uncertainty.
- Baseline simulations capture rapid drag rise at larger gap lengths.

M-GTS Body Force Coefficients at 6° Yaw



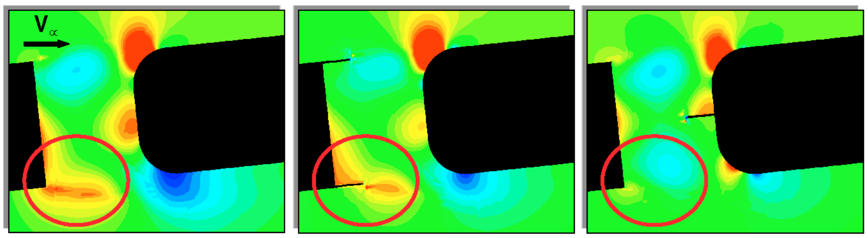
Simulated Devices Reduce Drag Through Two Primary Mechanisms

- Simulated devices decrease drag by:
  1) Reducing gap cross-flow
  2) Increasing tractor base pressure
- Tractor cab extenders realign the primary horseshoe vortex in the tractor-trailer gap.
- Trailer splitter plates creates a nearly-symmetric dual recirculation.
- The trailer splitter plate is more effective than cab extenders in reducing drag while maintaining side force.



Streamtraces colored by velocity magnitude

Both Aerodynamic Devices Decrease Tractor Drag and Increase Side Force

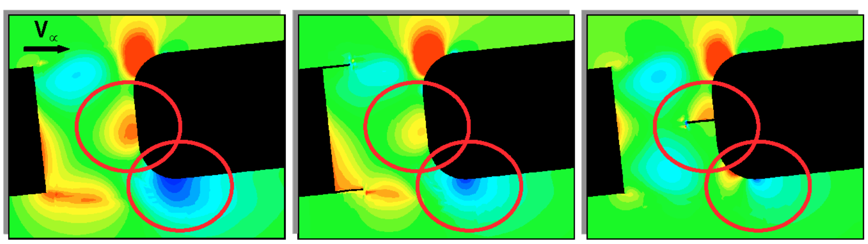


Pressure at 6° yaw and 0.65 gap

- Trailer splitter plates and tractor cab extenders decrease gap cross-flow by 30% and 50%
- Flow directed at the tractor base, increases pressure and decreases drag.
- Less cross-flow stagnates against the leeward shear layer, increasing tractor side force

DOE 51305-7

Both Aerodynamic Devices Decrease Trailer Drag and Side Force

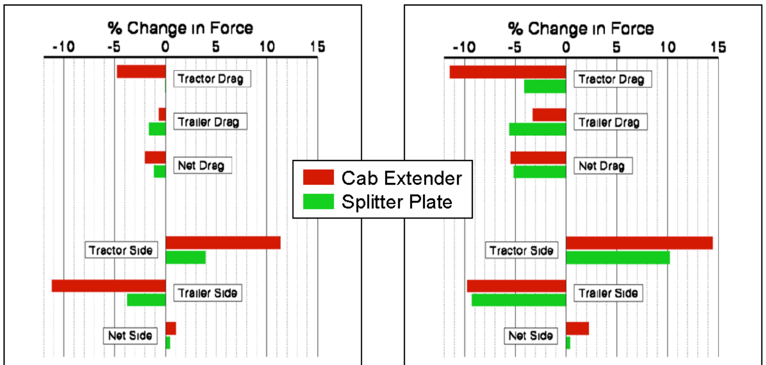


Pressure at 6° yaw and 0.65 gap

- Trailer splitter plates and tractor cab extenders decrease gap cross-flow by 30% and 50%
- Less flow impacts the trailer face, reducing pressure.
- The leeward shear layer is deflected less, resulting in higher pressures on the trailer side.

DOE 51305-8

The Trailer Splitter Plate is Effective at Reducing Drag at Low Reynolds Numbers



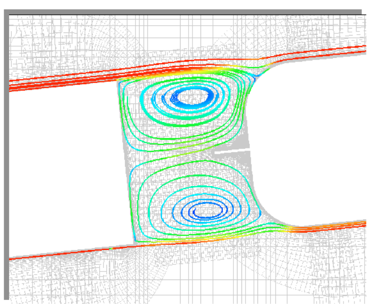
M-GTS with 0.35 length gap

M-GTS with 0.65 length gap

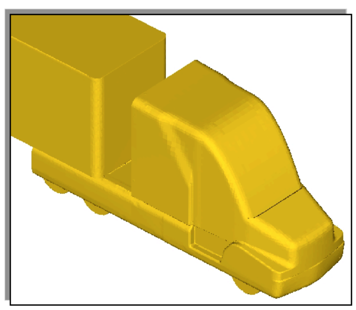
- The trailer splitter plate is nearly as effective as tractor cab extenders in reducing total vehicle drag, without a significant increase in side force.

DOE 51305-9

Extension to Full-Scale Reynolds Numbers Raises Additional Questions



Modified Ground Transportation System



Generic Conventional Model (GCM)

- It is unclear if the large radii of the trailer leading edges will affect the performance of the aerodynamic devices.
- The 3-D effects of an open gap-underside may be exacerbated at higher Reynolds numbers.

DOE 51305-10

Reducing the Aerodynamic Drag of Empty Coal Cars

Bruce L. Storms
James C. Ross, Dan Dzoan
NASA Ames Research Center
Kambiz Salari, LLNL
Working Group Meeting
Lawrence Livermore National Lab
May 13, 2005

Funded by the Department of Energy
Office of Heavy Vehicle Technology

Outline

- **Background**
- **Facility & Model**
- **Test Details**
- **Results**
- **Summary**

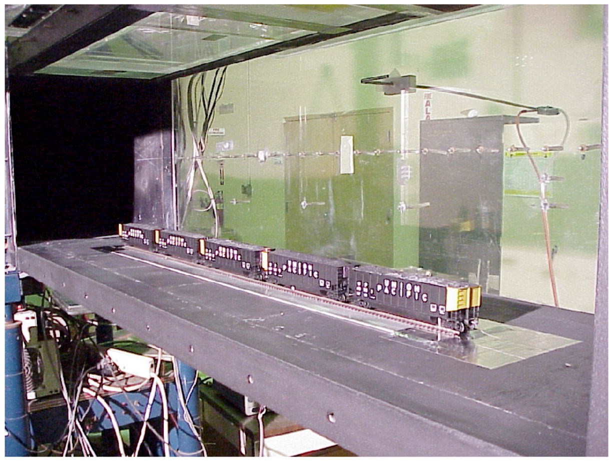
Background

- 2002 U.S. Statistics*
  - Coal provided 50% electricity
  - Total = 1 billion tons, 66% carried by rail
  - 44% tonnage, 25% loads, 21% revenue
  - 85% by unit trains (50+ cars)
  - Avg coal haul = 696 miles
- Aero Drag Reduction Potential
  - Fuel consumption: empty ≈ full
  - Aero drag ~ 15% of round-trip fuel consumption
  - 25% reduction –> 5% fuel savings (75 million gal)

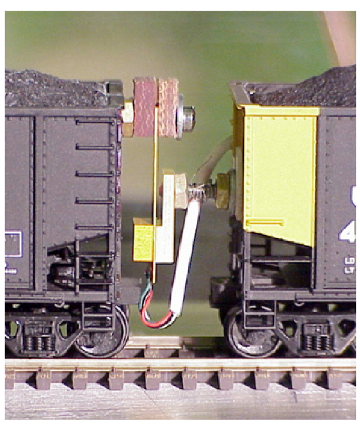
* The Rail Transportation of Coal, AAR, Vol. 5, 2003

15" x 15" Wind Tunnel

Model Installation

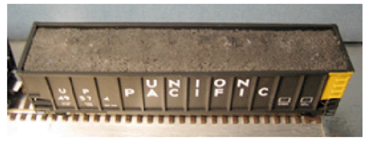


Test Details



- **Drag force measured using 2-lb load cell**
- **Test Conditions**
  - **Velocity = 65 m/s (145 mph)**
  - **Model Reynolds No. = 160,000 (full-scale Re = 3.9 million at 40 mph)**
  - **Critical Re = 10,000**
- **Yaw angles 0° to 10°**
- **Uncertainty:**
  - **1.0 - 1.5% for yaw ≤ 5°**
  - **2.5 - 4.9% for yaw > 5°**

Empty vs Full Cars



Yaw (ψ, deg)	C_D empty	C_D full	C_R empty	C_R full	% difference (full-empty)
0	**0.3334**	**0.2358**	**0.0924**	**0.0653**	**-29.3**
10	**0.6015**	**0.3519**	**0.1719**	**0.1006**	**-41.5**

$C_D = D / q^*A$ where $q = {}^1/_2\ \rho U^2$

$C_R = 1.0756\ \rho\ A\ C_D / \cos^2 \psi$, lb/mph^2

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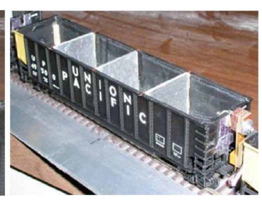
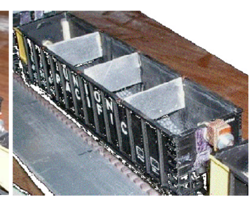
Cover & Divider Configurations

Cargo-bay Cover

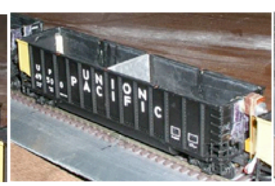


3 Full Dividers

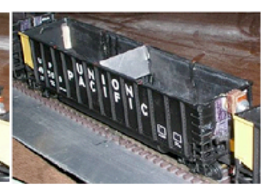


3 Half Dividers

Elevated Dividers



Single Full Divider



Single Half Divider

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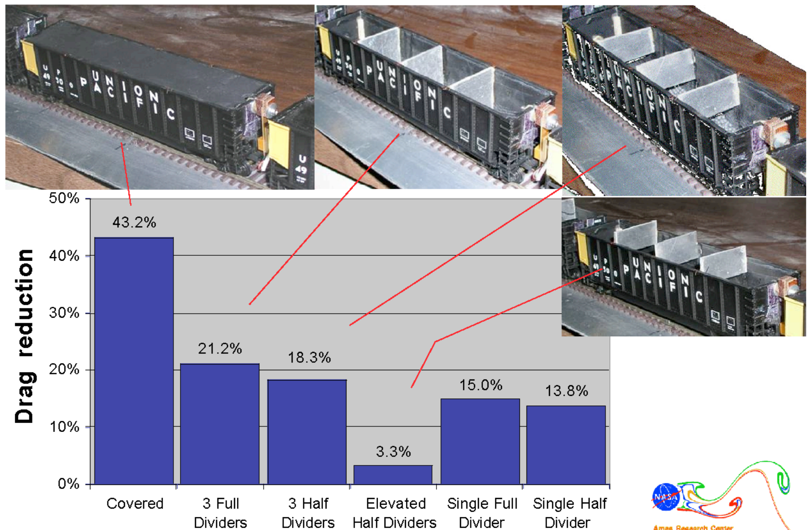
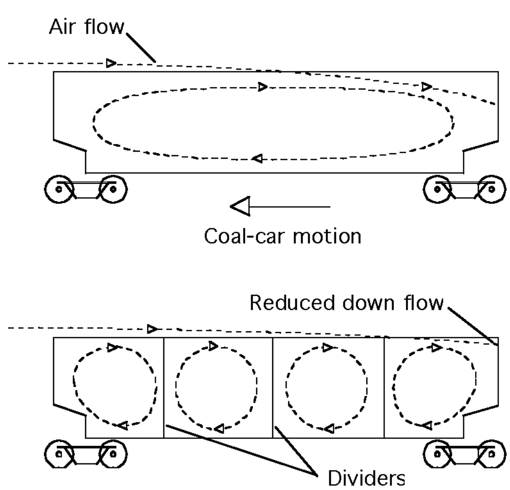
Cover & Divider Configurations

($\psi = 0$, no crosswind)



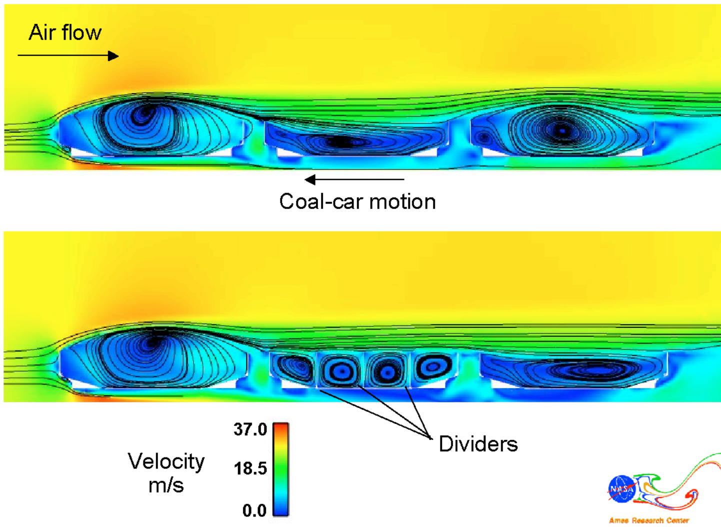
Experimental Physics Branch

Hypothesized Flow Field

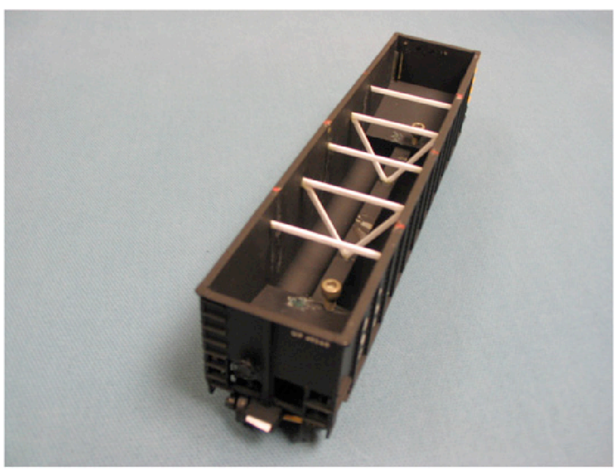


Experimental Physics Branch

Computed Flow Field

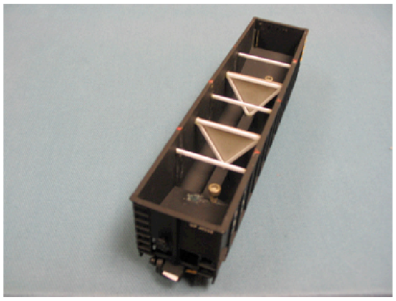


Internal Bracing

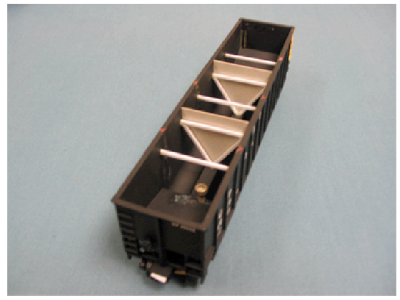


Experimental Physics Branch

Internal Bracing with Dividers



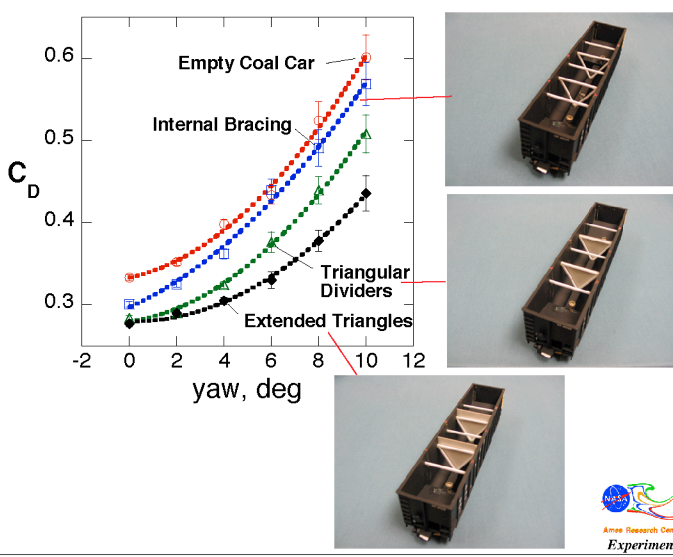
Triangular Dividers



Extended Triangles

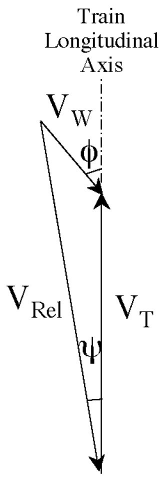
Experimental Physics Branch

Effect of Bracing & Dividers



Experimental Physics Branch

Wind-Averaged Drag, $\overline{C}_D$



$$\overline{C}_D(V_T) = 1/6 \sum_{j=1}^{6} M(j)\, C_D(j)$$

$$M(j) = 1 + (V_W/V_T)^2 + 2(V_W/V_T)\cos\phi(j)$$

$$\phi(j) = (j \times 30\ \text{deg}) - 15\ \text{deg}$$

$$C_D(j) = C_D \text{ at } \psi(j)$$

$$\psi(j) = \tan^{-1}\left[\frac{(V_W/V_T)\sin\phi_j}{1 + (V_W/V_T)\cos\phi_j}\right]$$

Mean wind speed, V_w = 7 mph

From SAE Recommended Practice, SAE J1252, 1981.

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Wind-Averaged Drag Example

Empty Coal Cars, Train Velocity = 40 mph

j	ϕ(j), deg	ψ(j), deg	M(j)	Cd(j)	M(j)Cd(j)
1	15	2.2	1.369	0.3569	0.4885
2	45	6.3	1.278	0.4541	0.5804
3	75	9.2	1.121	0.5660	0.6346
4	105	10.0	0.940	0.6057	0.5694
5	135	8.0	0.783	0.5175	0.4053
6	165	3.1	0.693	0.3725	0.2580

$$\overline{C}_D(40\ \text{mph}) = 1/6 \sum_{j=1}^{6} M(j)\, C_D(j) = 0.4894$$

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Wind-Averaged Drag & Resistance

Configuration	$\bar{C}_D$ wind-avgd	%diff	ΔR, lbs 100 cars, 40 mph
Empty	0.4894	0.0	0.0
Internal Bracing	0.4638	-5.2	-1133
Triangular Dividers	0.4118	-15.8	-3443
Extended Triangles	0.3661	-25.2	-5473

4340 lbs
= 463 hp

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Summary

- Zero-Crosswind Drag Reduction (relative to empty cars)
  - Full: 29%; Covered Car: 43%
  - Three full-height dividers: 21%
  - Two triangular dividers: 15% & 17%(extended)
- Wind-averaged Drag Reduction
  - Two triangular dividers: 16% & 25% (extended)

>> 25% reduction –> 5% fuel savings (75 million gal/yr)

>> Can be retrofit by attaching to internal bracing

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Future Work

- Larger scale testing
- Optimization
  - Dividers size, shape, location
  - Operational conditions / constraints
- Full-scale validation at TTC

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Effect of Train Length
(zero crosswind)

Configuration	Cd	% difference
2-1-2	0.2753	0.0
3-1-2	0.2664	-3.2
1-1-2	0.2996	8.8
2-1-1	0.2788	1.3

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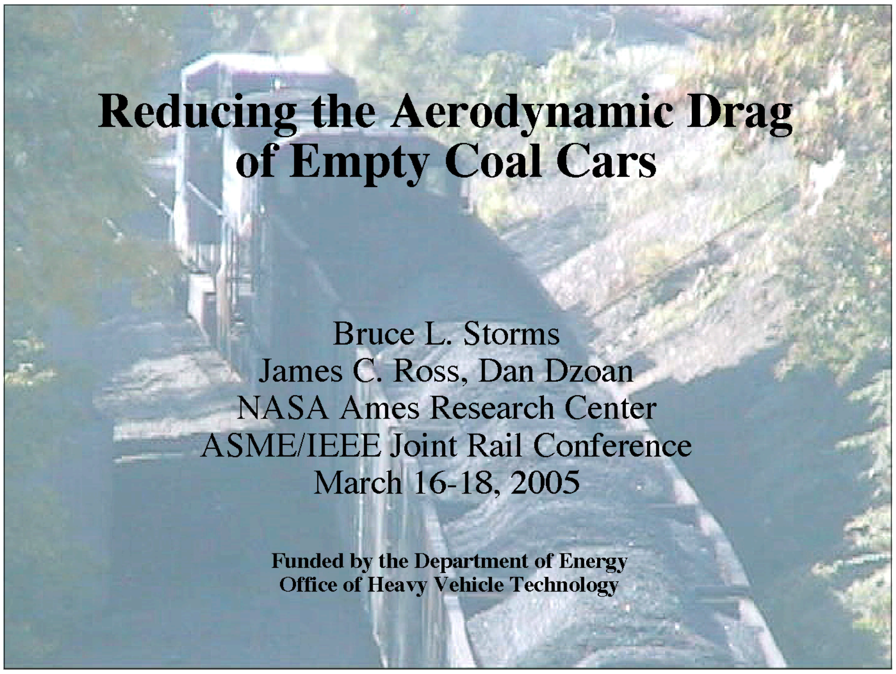

Reducing the Aerodynamic Drag
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THE UNIVERSITY OF TENNESSEE
SimCenter
AT CHATTANOOGA
Computational Simulation and Design Center

GRADUATE SCHOOL OF COMPUTATIONAL ENGINEERING

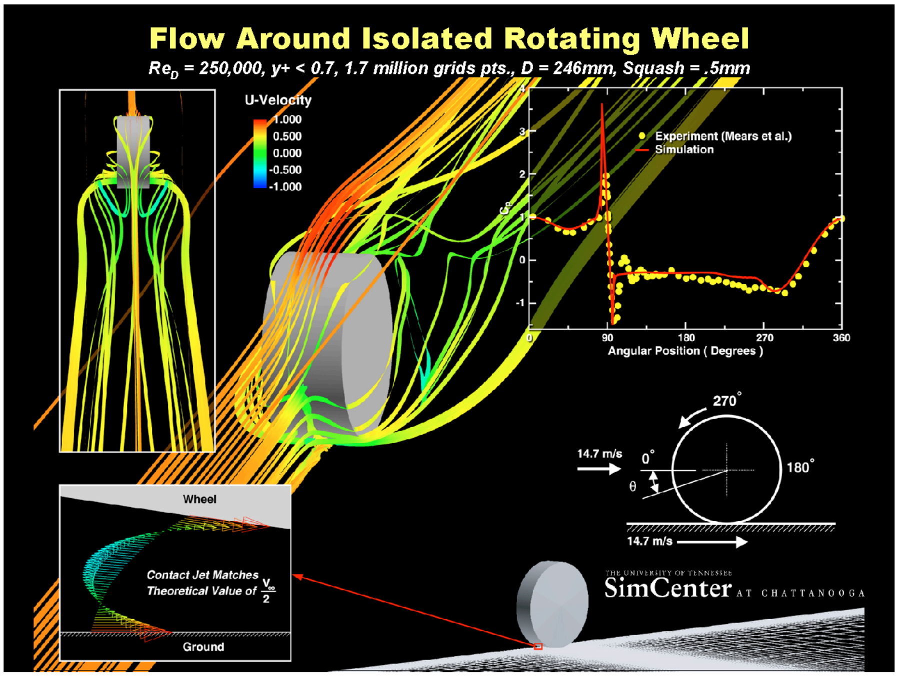
Tire Aerodynamics, Splash & Spray
Brake Cooling

Ramesh Pankajakshan

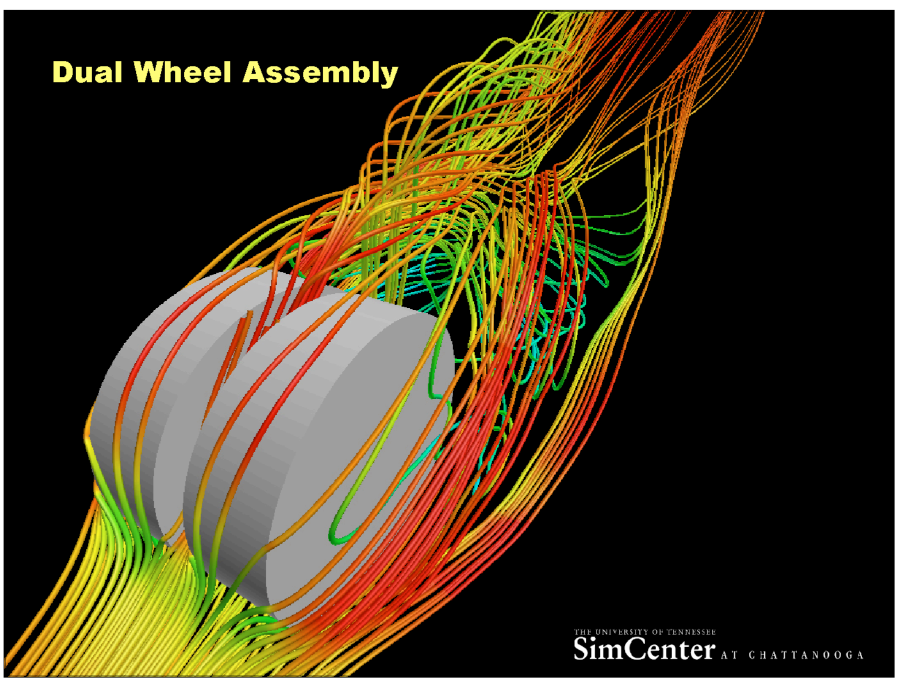
May 13, 2005

Objective

- Develop rotating wheel simulation capability
- Validate against experimental data
- Transition to full vehicle simulations



Flow Around Isolated Rotating Wheel
Re_D = 250,000, y+ < 0.7, 1.7 million grids pts., D = 246mm, Squash = .5mm
U-Velocity
1.000
0.500
0.000
-0.500
-1.000
Experiment (Mears et al.)
Simulation
Angular Position (Degrees)
270°
14.7 m/s
0°
θ
180°
14.7 m/s
Wheel
Contact Jet Matches Theoretical Value of V∞/2
Ground
THE UNIVERSITY OF TENNESSEE
SimCenter AT CHATTANOOGA



Dual Wheel Assembly
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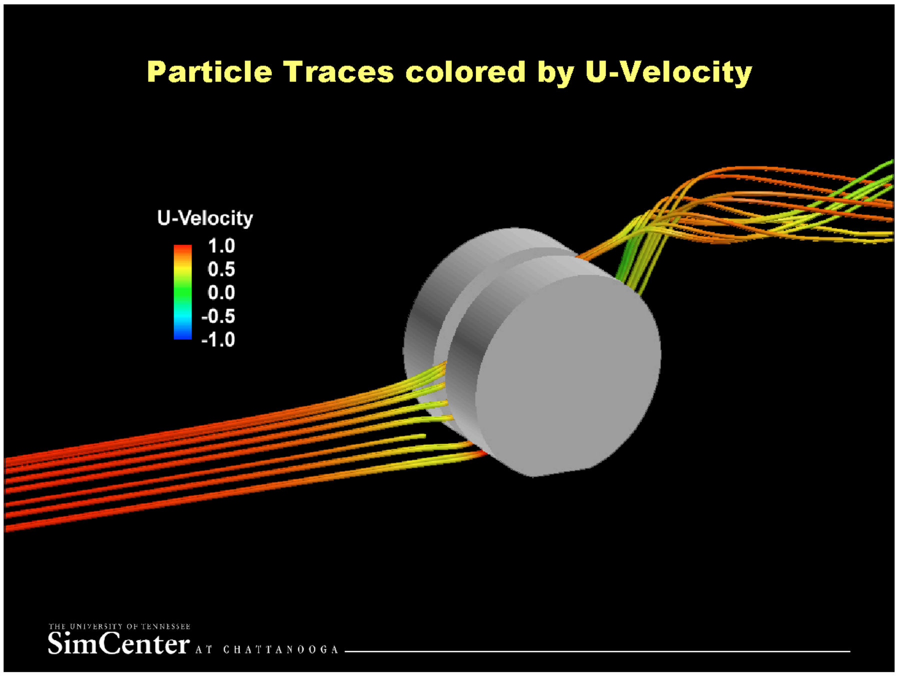
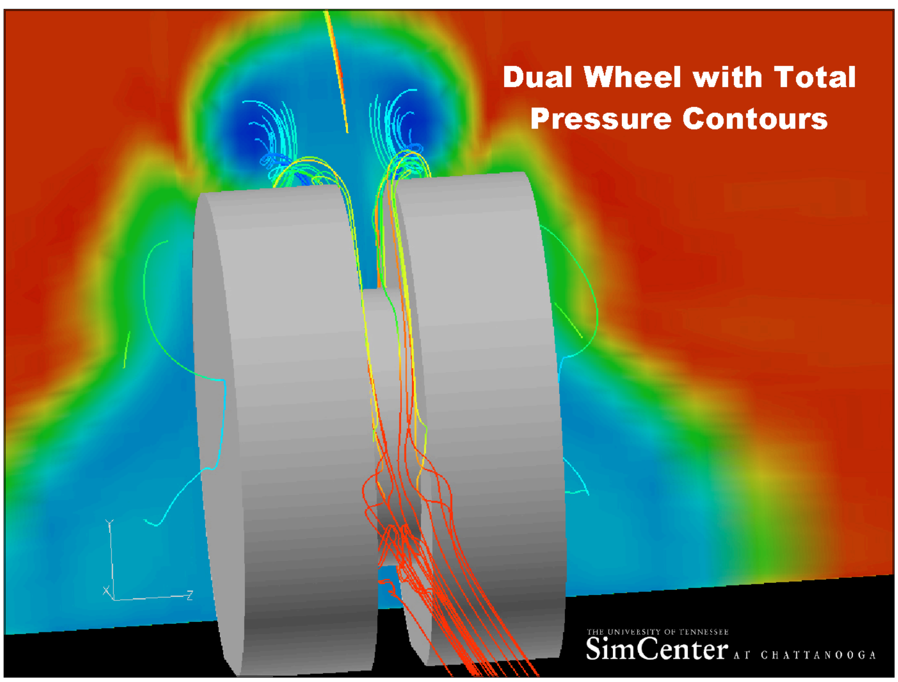
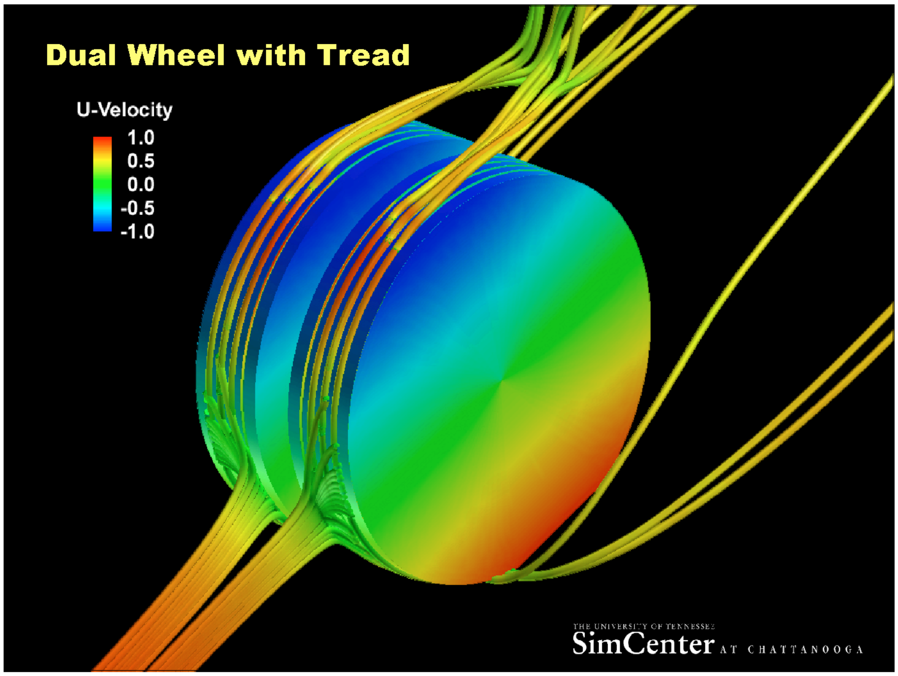
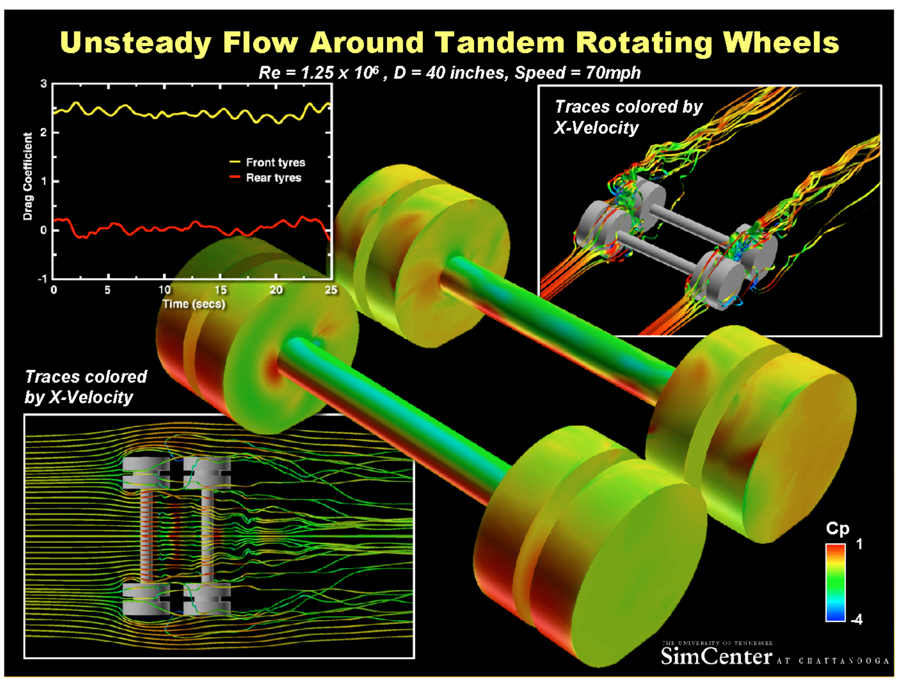
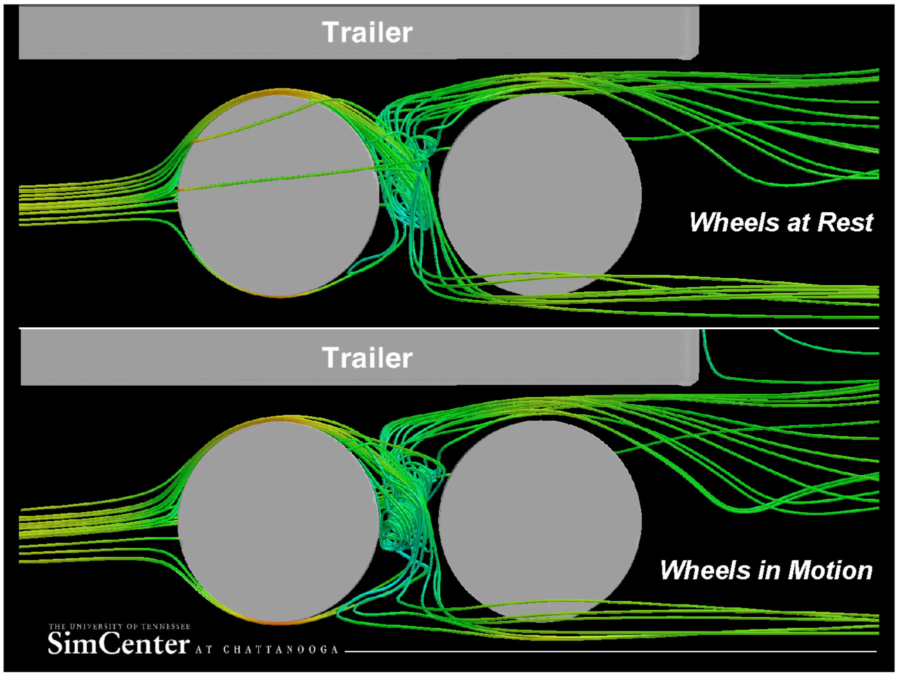
SimCenter AT CHATTANOOGA


Particle Traces colored by U-Velocity
U-Velocity
1.0
0.5
0.0
-0.5
-1.0
SimCenter AT CHATTANOOGA


Dual Wheel with Total Pressure Contours
SimCenter AT CHATTANOOGA


Dual Wheel with Tread
U-Velocity
1.0
0.5
0.0
-0.5
-1.0
SimCenter AT CHATTANOOGA


Unsteady Flow Around Tandem Rotating Wheels
Re = 1.25 x 10^6 , D = 40 inches, Speed = 70mph
Drag Coefficient
Time (secs)
Front tyres
Rear tyres
Traces colored by X-Velocity
Traces colored by X-Velocity
Cp
1
-4
SimCenter AT CHATTANOOGA



Splash & Spray

- Realistic geometry
  - Tread
  - Wheel Holes
  - Wheel Well/Trailer Underbody
  - Full Geometry

- Simulation effects
  - Large Grid Sizes
  - Relative Grid Motion
  - Large Simulation Time

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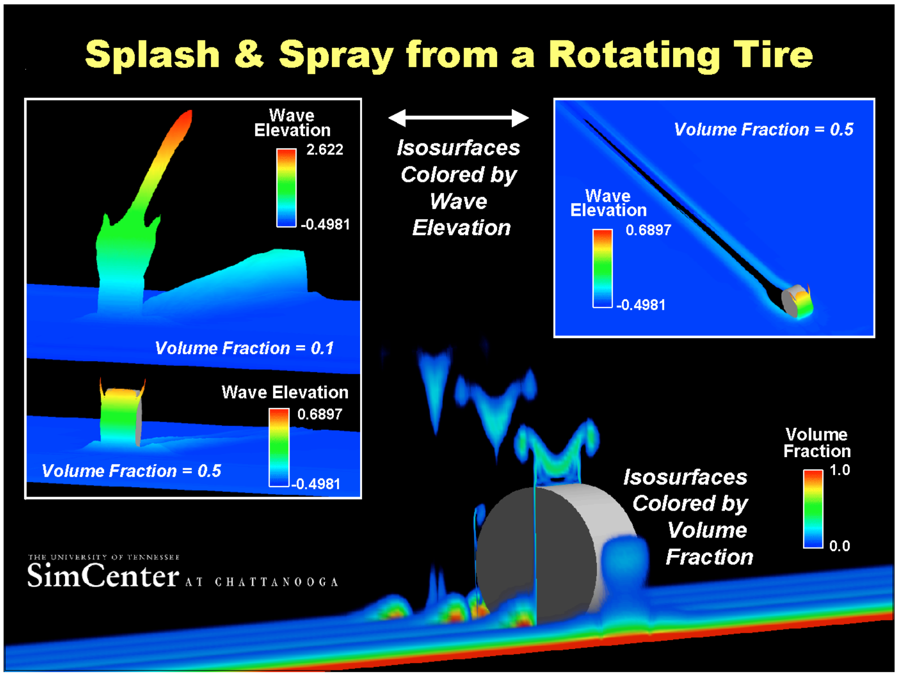
Splash & Spray from a Rotating Tire
Wave Elevation
2.622
-0.4981
Volume Fraction = 0.1
Wave Elevation
0.6897
-0.4981
Volume Fraction = 0.5
Isosurfaces Colored by Wave Elevation
Volume Fraction = 0.5
Wave Elevation
0.6897
-0.4981
Volume Fraction
1.0
0.0
Isosurfaces Colored by Volume Fraction
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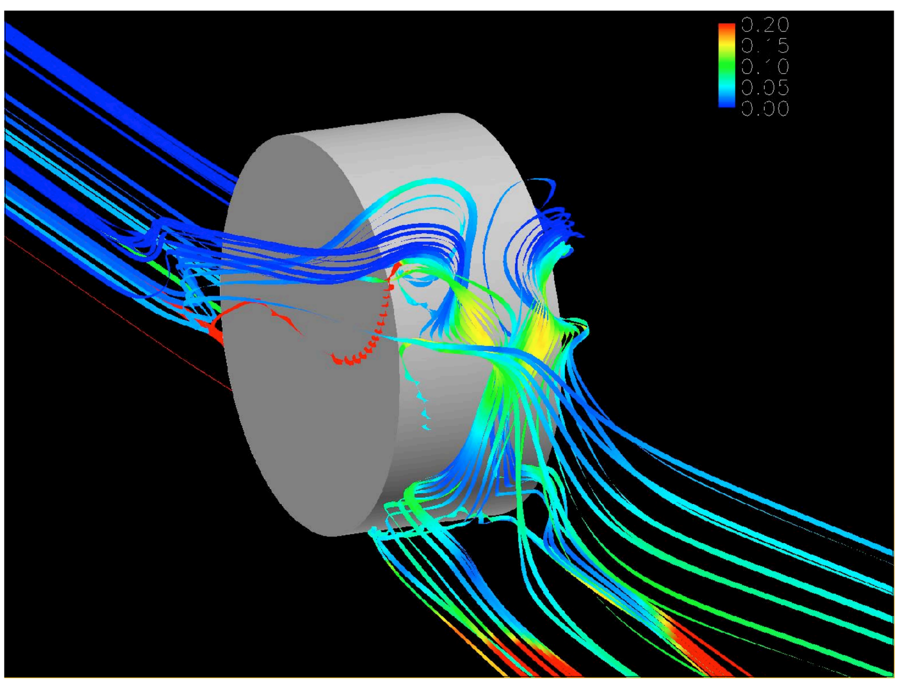
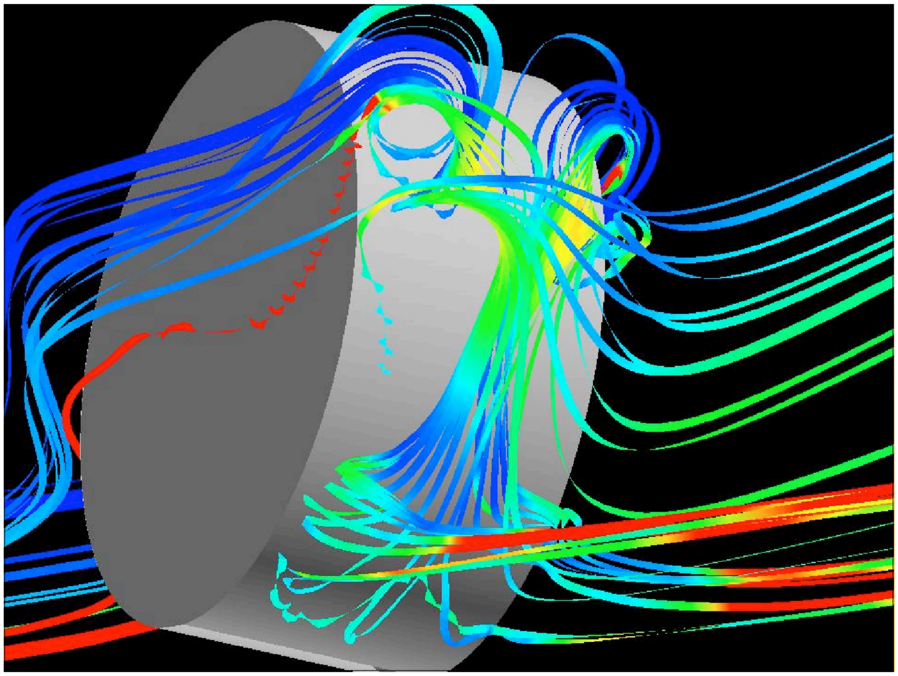

0.20
0.15
0.10
0.05
0.00



Brake Cooling

- Issues in brake cooling simulation
  - Relative Grid Motion
  - Buoyancy
  - Transition
  - Full Vehicle Simulation
  - Aero Braking Devices

THE UNIVERSITY OF TENNESSEE SimCenter AT CHATTANOOGA

Improving truck safety using computational tools

John Paschkewitz, Craig Eastwood, Jason Ortega

Lawrence Livermore National Laboratory

Heavy Vehicle Aero Consortium Meeting

May 13, 2005

Lawrence Livermore National Laboratory

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

Objectives and Accomplishments

Goal: "Investigate tire aerodynamics, study influence of wheel wells, and predict brake cooling performance"

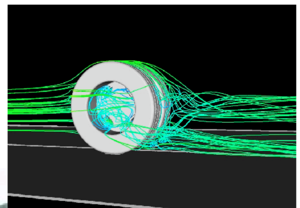
- Completed simulations of rotating cylinder and wheel (including treads & duals)
- Working on complex geometries

Goal: "Investigate state-of-the-art modeling capability in multi-phase flows to model splash and spray"

- Explored volume-of-fluid (VOF) methods for splash
- Completed spray simulations on realistic truck geometry, demonstrating key spray physics
- Established collaboration with Stanford Center for Turbulence Research (CTR)
  - Leveraged DOE/ASC investment to apply cutting-edge multiphase LES code (CDP) to splash & spray problem

Wheel and wheel well aerodynamics are essential to improving truck safety

Wheel and wheel well aerodynamics



http://www.odot.state.or.us/its/newsevents/Newsletter/news040101.htm

http://www.aaafoundation.org/e-news/issue6/splashspray.cfm

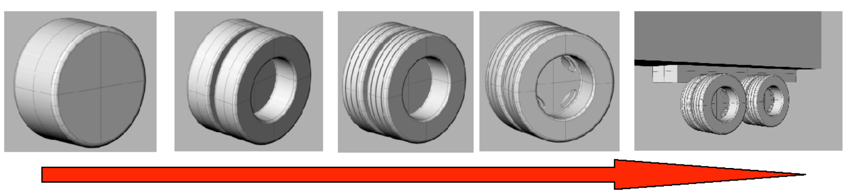
Brake cooling

Splash & Spray

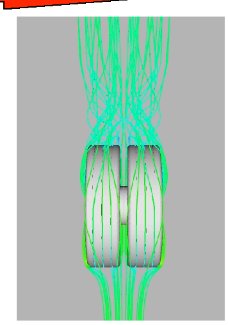
- **Focus on splash & spray**
- **Multiphase flow modeling introduces added complexity**

3

"Bottom up" approach to build confidence in wheel aerodynamics solutions



- **Using progressively more realistic models to capture wheel aerodynamics**
- **Simple models validated against available data**
- **Treads, tire shape and wheel important**
- **Meshing is challenging!**
  - **Consider immersed boundary (IB) approach when available in CDP this winter**



4

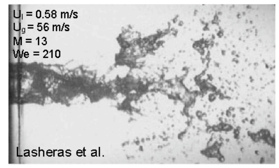
What is splash and what is spray?

Primary Atomization (splash)

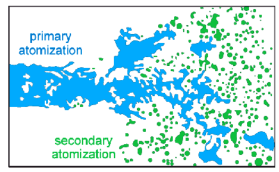
- **Initial breakup into large and small structures (ligaments/drops) close to the tire**
- **Complex interface topology of large scale coherent liquid structures**

NO rigorous models **describing primary breakup in turbulent environments**

Secondary Atomization (spray)



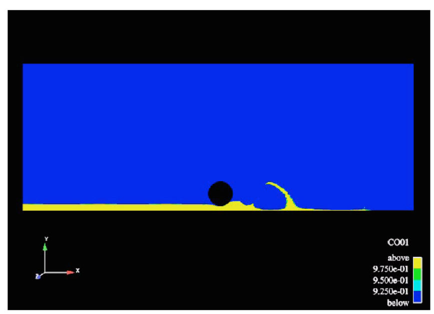
schematic



c/o Marcus Herrmann, Stanford/CTR

Splash modeling requires accurate interface tracking and coupling to spray

- StarCD uses the **Volume of Fluid (VOF)** approach
  - **VOF methods are well-accepted** and have good mass conservation properties
  - Solves single momentum equation for two fluids and tracks volume fraction of fluid in each cell
  - Surface tension effects accounted for using a "pseudo pressure"



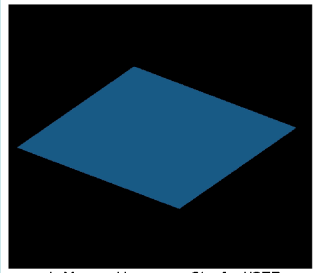
Result: 2D cylinder rotating above sheet of liquid flowing at 5 m/s

Issues:

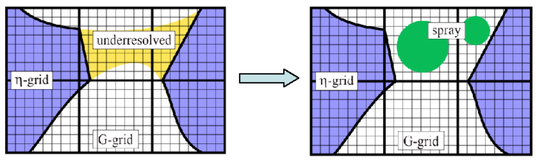
- **Interface reconstruction is not exact**
- **Coupling to spray calculations is not straightforward**
- **Need validation data! Fred Browand, other studies**

Looking ahead: Splash modeling with CDP

- CDP uses a **level-set** approach for interface tracking (Particle level set method (Enright, Fedkiw, Ferziger & Mitchell, 2002, *J.Comp.Phys.* 183)
- **Better interface capturing** than StarCD
- Largely DNS-focused at this time
- Developing a **novel method for coupling film-spray transition** using multiple grid methods
- Active research area at Stanford/CTR



c/o Marcus Herrmann, Stanford/CTR



Refined Level Set Grid (RLSG) method uses a coarse mesh (η-grid) and fine mesh (G-grid). Compare fluid-air interface on two grids to identify topology changes and define droplet formation events

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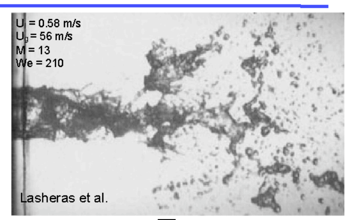
Spray modeling involves capturing breakup and dispersion

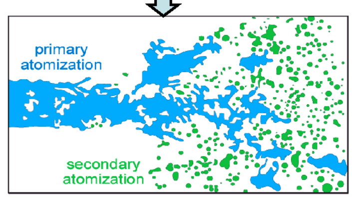
Primary Atomization (splash)

Secondary Atomization (spray)

- **Subsequent breakup into ever smaller drops forming a spray**
- **Simple geometry of small scale liquid drops (spheres) can be assumed**
- **Models for secondary breakup in turbulent environments exist (spray models)**



c/o Marcus Herrmann, Stanford/CTR



<u>Important non-dimensional parameter:</u>
Weber number (We) = ratio of fluid inertia (dynamic pressure) to droplet surface tension force

$$We = \frac{\rho V^2 D}{\sigma}$$

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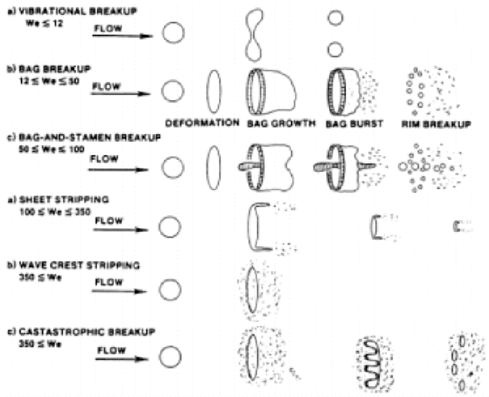
Droplet breakup mechanisms

Spray breakup models are
empirical
Breakup physics are complicated!

- StarCD uses several models, "best" is Pilch & Erdman model (1987)
- Drops break if We ~ O(10)



$$We = \frac{\rho V^2 D}{\sigma}$$ Carrier fluid inertia / Surface tension

From: Pilch and Erdman, Int. J. Multiphase flow, 13, p. 741-757, 1987 and http://www.aem.umn.edu/people/faculty/joseph/archive/docs/breakup99.pdf

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Do we expect droplet breakup?

What type of breakup do we expect and what is timescale for breakup?
Consider water drops with various diameters and slip velocity (difference between drop and air velocity) of 15 m/s:

Diameter (m)	We	Mode	Breakup time
5e-2	**188**	**Sheet stripping**	**0.4 sec**
1e-2	**38**	**Bag**	**0.1 sec**
1e-3	**3.7**	**NONE**	**NONE**

Conclusions:
- Large drops will break slowly relative to time in air
  - Ballistic trajectory takes ~ 0.1 sec to hit bottom of truck
- Small drops making up spray not likely to break!
- **Breakup largely due to collisions with truck surfaces**

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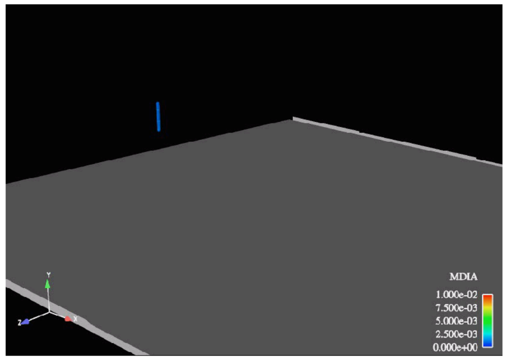
Droplet-surface collisions are critical and can be modeled

Collisions are essential to modeling spray production about truck

Active research area!

- Many empirical correlations
- Dry vs. wet surfaces important

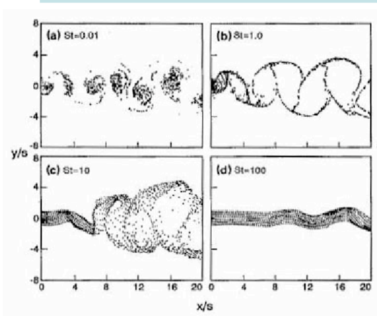


StarCD uses the Bai model (Bai & Gosman, SAE paper 950283, 1995) :

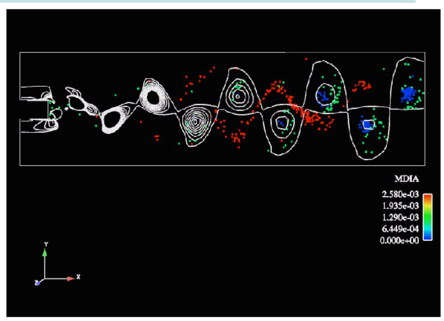
- Stochastic model that incorporates stick, spread, rebound and splash
- Assumes wetted wall (OK for truck)
- Daughter drop size/velocity depend on incident angle, droplet size and properties

Particle inertia impacts dispersion

- Particle inertia leads to important dynamic behavior!
- Important parameter is Stokes number (relative importance of particle to fluid inertia)
- If inertia is not too large (St < 10), see preferential concentration
  - Small particles get trapped in vortex cores
  - Larger particles get thrown towards outside of vortices



Tang et al, Phys. Fluids (1992)

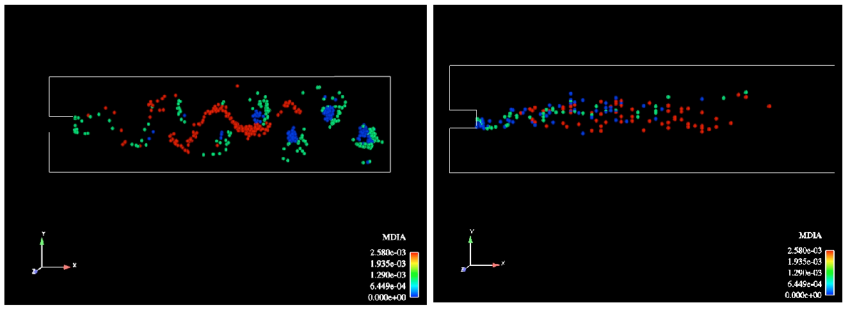


$$St = \frac{\tau_P}{\tau_F} = \frac{\rho_P d_P^{\,2} H}{18 \mu_C U}$$

Blue: St = 1e-3
Green: St = 0.1
Red: St =10

Dimensions and conditions:
Plane height H=2m(characteristic length)
Re = rUH/m=5100
U = 1 m/s, r=1 kg/m^3, m=1.96e-4 kg/ms

Steady-state simulations give incorrect dispersion



Unsteady RANS | Steady RANS

- Droplet behavior and flow field in steady RANS framework are simply WRONG!
- MUST use unsteady RANS/LES framework to correctly capture spray dispersion behavior

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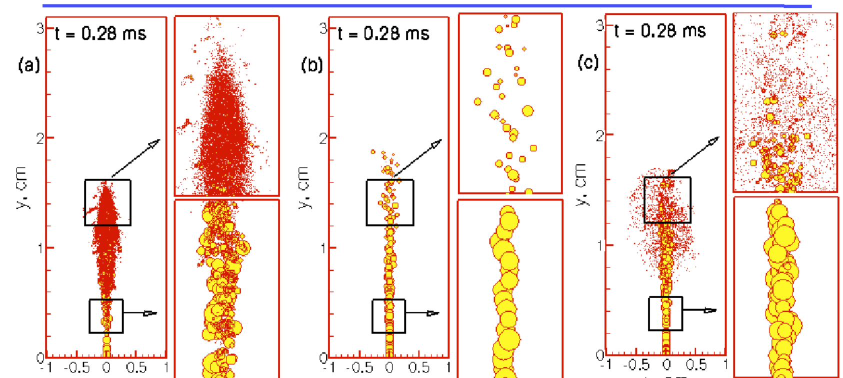
Computations: Droplet, Parcels, & Hybrid Approach



c/o S.V. Apte, Stanford, Int. J. Mult. Flow, 2003

Droplets (CDP) | Parcels (StarCD) | Hybrid (CDP)

- *Parcels* are used to manage computational cost but can be inaccurate
- Parcel = collection of identical-sized particles with constant mass
- Breakup increases the number of particles in a parcel, NOT number of parcels

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A computational model of truck spray

Details:

- Unsteady RANS, Re = 6E6, total time = 1.5 sec
- Rotating wheels
- Water droplets, uncoupled
- Injection velocity: 20-30 m/s
- 4.5L/s at 18 injectors
- 1000 parcels/sec
- 3 injection diameters
- Turbulent dispersion model
- Bai collision model
- Pilch & Erdman breakup

Findings:

- **No breakups observed in flow**
- **See drops "size segregate" in vortex motions**
- **Large velocities (30 m/s) required for small drops to get entrained in flow**
- **Drops in spray are approximately 100 microns in diameter**
- **Rich dynamics due to collision model around trailer wheels – film, breakage**

Looking ahead:

- **Need much clearer idea of droplet sizes and velocities making up spray! (INLET CONDITIONS?)**
- **Validation data is needed**

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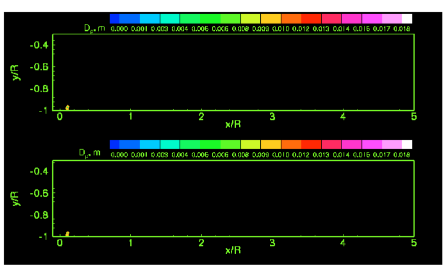
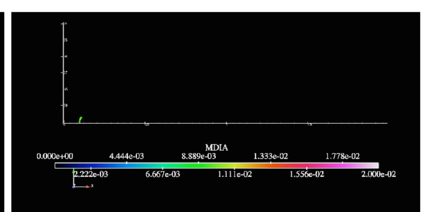
Looking ahead- spray modeling using LES/DES

Cross-flow atomization in turbulent channel flow at Re=10000
Jet-A droplets, injection velocity = 0.18 m/s, centerline velocity ~ 18 m/s



LES without (top) and with (bottom) coalescence



Unsteady RANS with coalescence

- Accurate spray calculation and visibility estimates require a LES/DES approach!
- Combination of parcels and URANS phase averaging removes important interactions with flow structures
- Working with Stanford CTR to model spray using CDP

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Conclusions

- LLNL has capability to investigate splash, spray and brake cooling
  - Completed detailed spray calculations
  - Preliminary splash calculations
  - Moving into brake cooling
- Generating database of wheel aerodynamics results central to all parts of problem
- Splash tools being investigated
  - VOF and level set using CDP
  - Interface tracking and coupling to spray challenging!
- Spray simulations in progress
  - Lagrangian particle tracking with URANS, parcels
  - Finite mass, collision models important
  - Need LES/DES to capture “billowing” and accurately estimate visibility reduction
- Need validation data for all parts of problem!

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Action Items

Technical

Get paper on measure of aero from tire load SAE 92-0346 (LLNL)
Duals vs singles SAE II test data from Bob E (Jules)
Check Kenworth/PACCAR website paper with recommendation on devices (LLNL)
Look at hula skirts - CFD-porous flexing plate, test- NRC. NASA (NASA)
Consider benefits for reducing drag for hybrid vehicles- UPS (USC, LLNL)
Address underhood cooling with aero-white paper, CRADA (NASA, LLNL)
Consider open grate at base of gap (LLNL)
Will baseflap and wedge counteract (LLNL)
Can flow be excited to improve baseflaps, effect of different flap angles (LLNL)
S&S with baseflaps and visibility of brake lights (LLNL)
Evaluate singularity points on rotating tire (UTC)

Action Items

Administrative

Gather all viewgraphs from meeting (ALL send to Rose)
SAE Conf Chicago in Nov
    Papers (ALL), Panel (Kambiz), Invite (Rose)
    Meeting with fleet owners, ATA (Rose)
Contribute to 21CTP white paper on aero
    Attend, present at aero merit review in Sept (Rose)
Join Marty F. at an ATA, TMC, or TMA committee meeting (Rose)
Sharing of DOE industry Consortium test plan (Sid)
Construct industry collaborative proposals to DOE’s 2007 RFP (ALL)
CRADA on wheel aero and S&S (USC, LLNL)
Industry insentives – talk to 21CTP, Ken Howden (Sid)
Visit other big fleet operators, Fedex, UPS (LLNL, USC, NASA, UTC)
Find the product engineers or decide if need national labs to design (LLNL)
Ask NRC to test effectiveness of devices for braking (LLNL)
Meet with rail companies, car manuf., power companies (NASA)
Meeting with DOT & Bill Knee (Sid)
Meeting with Vic Suski (Sid)
SOWs with conf calls, completed by June (Rose)
Suggest people for ECI meeting to Dave W. (ALL)